

General Disclaimer

One or more of the Following Statements may affect this Document

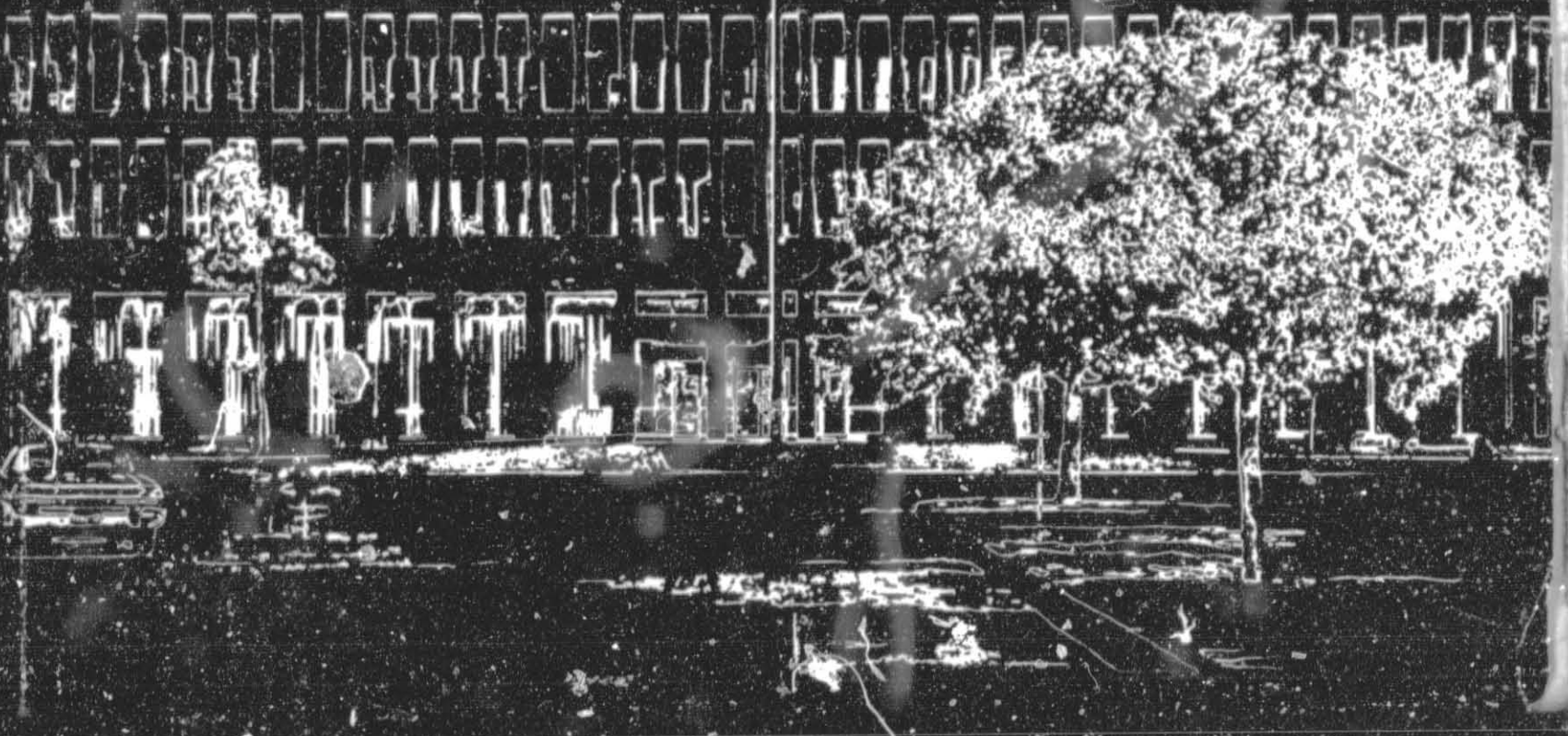
- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

(NASA-CR-168248) APPARATUS ANALYSIS AND
PRELIMINARY DESIGN OF LOW GRAVITY POROUS
SOLIDS EXPERIMENT FOR STS ORBITER MID-DECK
Final Report, Dec. 1981 - Oct. 1983 (TRW,
Inc., Redondo Beach, Calif.) 258 p

N84-10109

Unclass

G3/12 42316



1. Report No. NASA CR 168248		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle APPARATUS ANALYSIS AND PRELIMINARY DESIGN OF LOW GRAVITY POROUS SOLIDS EXPERIMENT FOR STS ORBITER MID-DECK				6. Report Date October 1983	
				8. Performing Organization Code	
7. Author(s) R.D. Fleeter, N. Gat and J.L. Kropp				8. Performing Organization Report No. 38884-6001-UT-00	
9. Performing Organization Name and Address TRW Space and Technology Group One Space Park Redondo Beach, CA. 90278				10. Work Unit No.	
				11. Contract or Grant No. NAS 3-23254	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				13. Type of Report and Period Covered Final 12-81 to 10-83	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract This report describes the apparatus analysis laboratory equipment design and fabrication and the preliminary design of the Combustion of Porous Solids Experiment for operation in the mid-deck area of the Shuttle. The apparatus analysis indicated that the mid-deck region of the STS was a feasible region of the Shuttle for operation. A sixteen tube concept was developed with tubes of 75 cm length and up to 5.6 cm accommodated. The experiment is viewed by IR sensors and a 16 mm camera. Laboratory equipment was designed and fabricated to test the particle injection, mixing and venting concepts. This equipment was delivered to NASA/LeRC. A preliminary design was made for the experiment based upon the apparatus analysis. The design incorporated results from the Phase "O" Safety Review. This design utilizes a closed tube concept in which the particles are stored, injected and burned with no coupling to the Shuttle environment. Drawings of the major components and an assembly are given. The electronics are described for the experiment. An equipment list is presented and an experiment weight estimate is determined. The mission operation requirements are outlined.					
17. Key Words (Suggested by Author(s)) Mid-Deck Experiment Combustion Particle Burning Low Gravity Research Shuttle Experiment Design				18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 270	
				22. Price*	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

TABLE OF CONTENTS

	Page
FOREWARD	vi
ABSTRACT	vii
1.0 INTRODUCTION	1-1
1.1 Experiment Concept	1-5
1.2 Design Approach	1-5
2.0 SYSTEM REQUIREMENTS	2-1
2.1 Science Requirements	2-1
2.2 Mid-Deck Accomodation	2-6
2.2.1 Mid-Deck Experiment Arrangements	2-7
2.3 Experiment Development Approach	2-13
3.0 APPARATUS ANALYSIS	3-1
3.1 Combustion Tube	3-2
3.1.1 Tube Material	3-4
3.1.2 Tube Wall Thickness	3-4
3.1.3 Tube Mass	3-9
3.2 Combustion Tube Support	3-9
3.3 Combustion Product Venting	3-11
3.3.1 Venting Requirements	3-11
3.3.2 Product Gas Volume	3-13
3.3.3 Vent Systems	3-14
3.3.4 Vent Concept	3-21
3.4 Particle Introduction	3-23
3.5 Particle Mixing	3-25
3.5.1 Mechanical Mixing	3-27
3.5.2 Acoustic Mixing	3-28
3.5.3 Aerodynamic Mixing	3-31
3.5.4 Low Gravity Considerations	3-32
3.5.5 Conclusions	3-32
3.6 Ignition	3-33
3.6.1 Spark Discharge	3-33
3.6.2 Preflame Ignitor	3-34
3.7 Instrumentation	3-35
3.7.1 Photography	3-36

TABLE OF CONTENTS (cont.)

	Page
3.7.2 Particle Homogeneity	3-40
3.7.3 Flamefront Sensing	3-40
3.7.4 Accelerometers	3-41
3.8 Data Acquisition	3-42
3.9 Thermal Control	3-43
3.10 Combustion of Porous Solids Experiment Concept	3-43
4.0 LABORATORY EQUIPMENT DEVELOPMENT	4-1
4.1 Simulation Objectives	4-2
4.2 Laboratory Equipment Components	4-3
4.2.1 Combustion Tube	4-5
4.2.2 Particle Injector	4-5
4.2.3 Particle Mixer	4-7
4.2.4 Ignition	4-10
4.2.5 Combustion Gas Venting	4-11
4.2.6 Flame Shape, Speed and Detection	4-13
5.0 COPSE SUBSYSTEM DESIGN	5-1
5.1 Combustion Tube	5-1
5.2 Particle Injector	5-7
5.3 Particle Mixing	5-11
5.4 Ignitor	5-11
5.5 Combustion Gas Vent	5-12
5.6 Instrumentation	5-17
5.6.1 Camera	5-17
5.6.2 Flame Sensors	5-17
5.6.3 Mixing Sensors	5-18
5.6.4 Accelerometer	5-21
5.7 Thermal Control	5-21
5.8 Electronics	5-21
5.8.1 Front Panel	5-21
5.8.2 Controller	5-24
5.8.3 Data Acquisition and Recording	5-28
5.8.4 Acoustic-Driver	5-30
5.8.5 Secondary Power Supplies	5-30
5.8.6 Electromagnetic Compatability	5-32
5.9 Structures	5-34

TABLE OF CONTENTS (cont.)

	Page
5.9.1 Assembly Structure	5-34
5.9.2 Carousel Structure	5-34
5.9.3 External Housing	5-35
6.0 LAYOUT AND EQUIPMENT	6-1
6.1 Mechanical Layout	6-1
6.2 Equipment List	6-2
6.3 Weight Estimate	6-2
6.4 Electrical Requirements	6-5
7.0 MISSION OPERATION	7-1
7.1 Crew Interaction	7-1
7.2 Time Line	7-2
8.0 EXPERIMENT SAFETY	8-1
9.0 EXPERIMENT STATUS	9-1
9.1 Experiment Requirements	9-1
9.2 Technical Testing	9-4
9.3 Design Issues	9-5
9.4 Safety Constraints	9-6
10.0 REFERENCES	10-1
APPENDIX 1 Heat Sink Mass Selection	A1-1
APPENDIX 2 Energy of Gas Storage/Mass/ Complications Comparison	A2-1
APPENDIX 3 Mechanical Mixer Performance Analysis	A3-1
APPENDIX 4 Acoustic Mixer Program Selection	A4-1
APPENDIX 5 Acoustic Loss Calculation	A5-1
APPENDIX 6 Aerodynamic Mixer Design Analysis	A6-1
APPENDIX 7 Particle Size Scaling Analysis	A7-1
APPENDIX 8 Optical Scattering by Fuel Particles,	A8-1
Sensor Output Interpretation	
APPENDIX 9 Laboratory Equipment Operating	A9-1
Instructions and Parts List	
APPENDIX 10 Safety Hazard Reports	A10-1
APPENDIX 11 Summary of Discussions at Final	A11-1
Briefing (8/10/83)	

LIST OF TABLES

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
2.1	Shuttle Mid-Deck Accomodations	2-9
2.2	Initial Mid-Deck Constraints/Conditions	2-15
2.3	Comparison of Common & Individual Functions In the Copse	2-17
3.1	Qualities of Combustion Tube Candidate Materials	3-5
3.2	Comparison of Single Rechargeable Tube vs Multiple Precharged Tubes	3-10
3.3	Vent Systems	3-16
3.4	Data Acquisition System	3-36
4.1	Requirements and Capabilities of The Laboratory Equipment	4-4
5.1	Table Components	5-7
5.2	Injector Components	5-8
5.3	Mixer Components	5-12
5.4	Combustion Experiment EMI Analysis	5-33
6.1	Equipment List	6-3
6.2	Porous Solids Experiment Weight Estimation	6-5
6.3	Copse In-Flight Power Requirements	6-6
7.1	Timeline for Carrying Out Combustion Tube Experiment	7-2
9.1	Copse Requirements vs Experiment Design Capabilities	9-2

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Combustion of Porous Solids Experiment -- Professor A. L. Berland	1-3
1.2	Copse Design Approach	1-6
2.1	Science Requirements	2-3
2.2	Concentration Range	2-5
2.3	Experiment Operation	2-6
2.4	Mid-Deck Location in the Space Shuttle	2-8
2.5	Mid-Deck Area Arrangement	2-8
2.6	Mid-Deck Development Through Preliminary Design	2-14
2.7	Mid-Deck Locker Configurations Considered	2-16
3.1	Combustion of Porous Solids Experiment - Function Flow	3-3
3.3	Copse Carousel Concept	3-11
3.4	Venting Concepts	3-17
3.5	Open Scrubber Concept	3-19
3.6	Typical Open Vent Concept	3-20
3.7	Fuel Injector System	3-25
3.8	Copse Mixing Concept	3-26
3.9	Acoustic Mixer Design	3-29
3.10	Optical System Concept	3-38
3.11	Film Use Budget: Film Speed = 100 Frames/Sec	3-39
3.12	Particle Operating Envelope for Scattering	3-41
3.13	Combustion Tube Concept	3-44
3.14	Copse Carousel Concept	3-45
4.1	Laboratory Combustion Tube Dimensions	4-6
4.2	The Flame Tube Mounted on the Apparatus Baseplate	4-6
4.3	Laboratory Particle Injector	4-7
4.4	Laboratory Mixing Systems	4-8
4.5	Acoustic Driver Mounted to the Combustion Tube	4-9
4.6	External Fan in Place at Tube End Before Enclosure by Shroud	4-11
4.7	Laboratory Venting Schematic	4-12
4.8	Complete System Ready for Vent Testing	4-12
4.9	Typical Sensor Data From Laboratory Test	4-15
5.1	Copse Combustion Tube	5-3
5.2	Copse Vent System	5-5
5.3	Particle Injection System	5-9
5.4	Copse Experiment Layout	5-13
5.5	Copse Vent Detail	5-15
5.7	Operator Display of Particle Mixing	5-18
5.6	Copse Optical System	5-19
5.8	Composition Experiment Electronic Block Diagram	5-22
5.9	Copse Front Panel Display Functions	5-23
5.10	Typical Front Control Panel	5-25
5.11	Controller Functional Diagram	5-26
5.12	Typical Driver Operation	5-27
5.13	Copse A/D Convert Schematic	5-29
5.14	Typical Acoustic Driver Circuit	5-31
5.15	Copse Support Structure Isometric	5-37
5.16	Copse Support Structure	5-39

FOREWARD

This program was initiated by NASA/Lewis Research Center. It forms part of the combustion experiment program that is being conducted through LeRC. This study was conducted in essentially two phases; apparatus analysis and laboratory equipment development and preliminary design. The major participants in the Apparatus Analysis Phase were:

Mr. Richard DeWitt, LeRC Program Manager

Dr. Nahum Gat, TRW Program Manager

Significant contributions to that program were made by Mr. Thomas S. Kolesar and Mr. Shell Noreen. In the laboratory equipment design and preliminary design principal contributors were:

Mr. Ralph Nussle, LeRC Program Manager

Dr. John L. Kropp, TRW Program Manager

Dr. Richard D. Fleeter, Laboratory Equipment Design and Analysis

Mr. George Dosa, Design.

Significant contributions were made by Dr. Gat in analysis; Mr. John Hill in electronics and Mr. Dale Waldo in safety.

ABSTRACT

This report describes a program performed as part of the development of the Combustion of Porous Solids Experiment for operation in the STS. The specific tasks include:

- Apparatus Analysis
- Laboratory Equipment Design and Fabrication
- Preliminary Design

The apparatus analysis resulted in a mid-deck location for the experiment operation. A sixteen tube carousel concept was developed. The appropriate subsystems were analyzed for closed tube vs open tube operation. The analyses resulted in several technical issues that were best resolved by development testing. Laboratory equipment was designed and fabricated to test the most significant subsystems. The laboratory equipment was delivered to LeRC where it was tested.

A preliminary design was generated based upon the results of the apparatus analysis and test results. Early design consideration featured common support subsystems to the combustion tube. However, a Phase "O" Safety Review held at JSC resulted in a "closed tube" design. The current preliminary design features experiments that are closed. Each combustion experiment is self-contained including individual injector mechanism, ignition and venting. Mixing and instrument subsystems are common. The design approach is compatible with mid-deck operation in four vertical lockers and meets STS weight requirements. Layouts and configuration arrangements for the hardware are presented.

1.0 INTRODUCTION

Lewis Research Center (LeRC) has developed a program for conducting combustion science experiments in Space. A series of experiments have been developed for operation on the Space Shuttle. Originally, these experiment concepts were configured to operate within a facility in the Spacelab module. Experiment requirements and operation were consistent with Spacelab operation. It is now known that early flight of several experiments can be most efficiently achieved if they are configured to be flown separately in a location other than a Spacelab facility. The mid-deck locker area of STS is such a location where individual experiments can be carried out. A program has been undertaken to develop experiment hardware for such mid-deck experiments.

One experiment is the Combustion of Porous Solid Experiments (COPSE) which was conceived by Prof. A Berlad. Essentials of Dr. Berlad's experiment are given in Figure 1.1. The experiment program has gone through three phases in development.

This report presents the results of a study of :

- a) The apparatus analysis for implementing COPSE.
- b) The design and fabrication of laboratory hardware for LeRC test.
- c) The preliminary design of the experiment for mid-deck operation.

The report assembles the information from these three major tasks. The study segments are presented as parts of an integrated whole.

A. EXPERIMENT OBJECTIVE

COMBUSTIBLE PARTICLES ARE BURNED IN AN OXIDIZING ATMOSPHERE

CLARIFY THE MECHANISMS OF QUASI-STEADY FLAME PROPAGATION AND EXTINCTION IN HOMOGENEOUS MIXTURES OF PREMIXED, FINELY DIVIDED, COMBUSTION PARTICULATES IN AN OXIDIZING GASEOUS ATMOSPHERE.

B. EXPERIMENTAL PROCEDURE

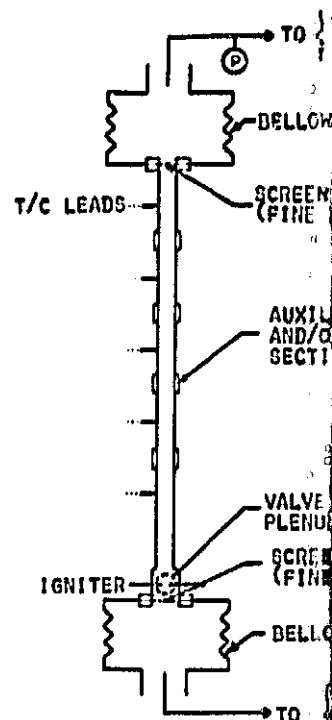
- INSERT PREPACKAGED TUBE INTO FACILITY
- SHAKE TUBE TO UNIFORMLY DISPERSE PARTICLES
- VERIFY PARTICLE UNIFORMITY USING LASER AND DETECTOR
- ACTIVATE INSTRUMENTATION
- IGNITE MIXTURE AT ONE END
- RECORD TUBE TEMPERATURE AS FLAME PROPAGATES
- REMOVE PREPACKAGED TUBE
- REPEAT EXPERIMENT WITH A DIFFERENT TUBE

C. DATA OUTPUT

- LASER DETECTOR SIGNAL (INITIAL)
- TEMPERATURE VS. POSITION AND TIME
- FILM RECORD
- EVENT TIME CORRELATION
- CHAMBER PRESSURE

D. APPARATUS CONFIGURATION

ORIGINAL PAGE IS
OF POOR QUALITY



E. TEST MATRIX

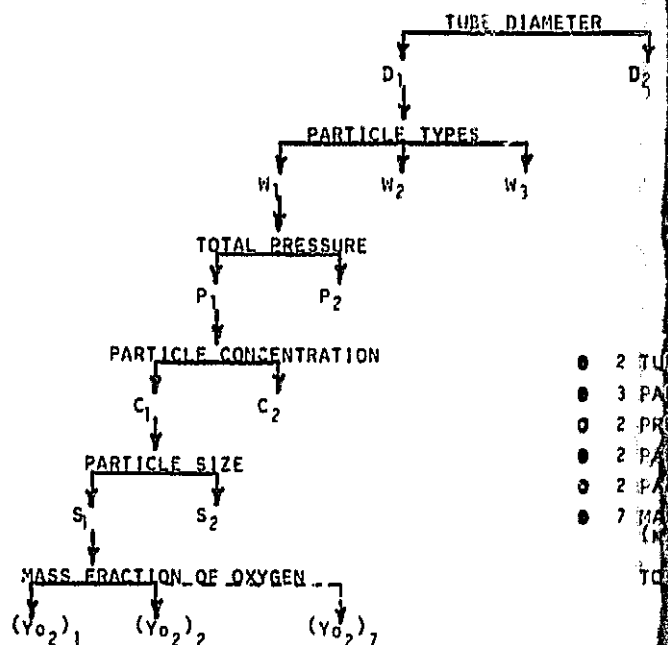
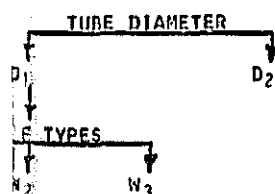
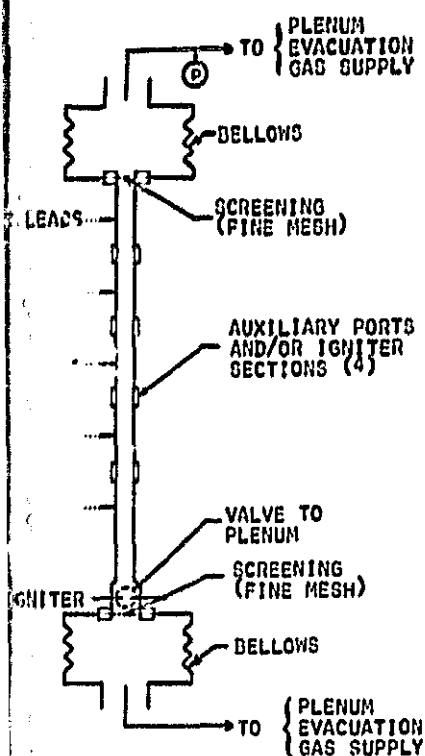


Figure 1.1 Combustion of Porous Solids Experiment



- 2 TUBE DIAMETERS D_1
- 1 PARTICLE TYPES W_1
- 2 PRESSURES P_1
- 2 PARTICLE CONCENTRATIONS C_1
- 2 PARTICLE SIZES S_1
- 7 MASS FRACTIONS OF OXYGEN (Y_{O_2})₁ (N_2/O_2 RATIOS)

TOTAL TEST RUNS - 336

F. CRITICAL PARAMETERS

- DEGREE OF PARTICLE UNIFORMITY OVER TEST LENGTH
- PHOTOGRAPHIC FILM FRAMING RATE
- TEMPERATURE MEASUREMENT ACCURACY

ORIGINAL PAGE IS
OF POOR QUALITY

G. INTERFACED WITH FACILITY

- ELECTRICAL
 - IGNITION SYSTEM
 - TEMPERATURE SENSORS
- MECHANICAL
 - UNIFORM CLOUD GENERATION HARDWARE
- PNEUMATIC
 - GAS SUPPLY AND CONTROLS
- VENT SYSTEM
- OPTICAL
 - CAMERA
 - LASER AND DETECTOR
- DATA HANDLING AND CONTROLS

H. ISSUES

- MINIMUM TUBE LENGTH REQUIRED
- TIME REQUIRED TO PERFORM TEST MATRIX
- ATTAINMENT OF UNIFORM PARTICLE CONCENTRATION
- MAINTENANCE OF TUBE PRESSURE DURING EXPERIMENT
- IGNITION SYSTEM
- REQUIRED EXPERIMENT FIELD OF VIEW FOR CAMERA VIEWING

2 FOLDOUT FRAME

1.1 EXPERIMENT CONCEPT

The experiment concept was evolved by Dr. A. Berlad. The experiment consists of burning a known concentration of suspended particles in air. The experiment is conducted in a combustion tube and the entire operation is maintained in a confined volume. The tube length and diameter and the resultant volume are fixed. The number and type of particles are varied with each experiment.

The experiment as originally conceived was to operate within the combustion facility in Spacelab. The effort in this study is directed to implementing the experiment in mid-deck. This resulted in additional constraints in areas including weight, size and venting compared to the original concept.

1.2 DESIGN APPROACH

The approach used in deriving the design is diagrammed in Figure 1.2. The inputs to the effort are listed as inputs to this table. They consist of Dr. Berlad's report; report of the study performed to assess the proposed combustion facility in which the requirements for each experiment were determined; and the NASA documentation concerning STS design guidelines. The requirements form the basis of the design development in this program.

In Section 2.0 the scientific requirements are derived and the requirements in the experiment design to meet these requirements in mid-deck assessed. The mid-deck constraints are also evaluated. The conceptual design and subsystems are discussed in Section 3.0. The method of development and their capabilities are evaluated. Section 4.0 summarizes the test equipment that was fabricated for use by LeRC in their test

PRECEDING PAGE BLANK NOT FILMED

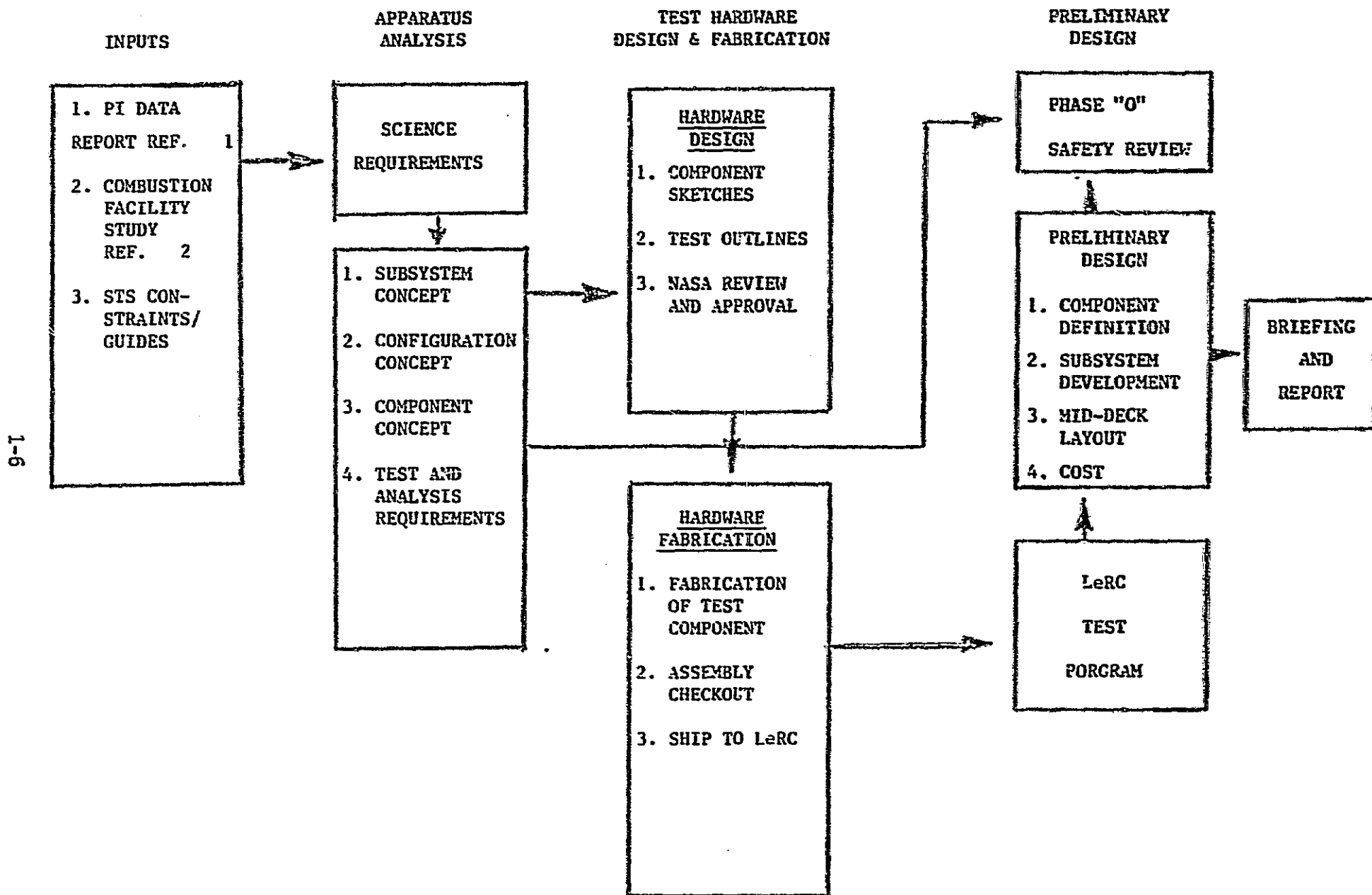


Figure 1.2 COPSE DESIGN APPROACH

program. The preliminary design that was derived is given in Section 5.0. The layout and equipment lists are given in Section 6.0. Section 7.0 reviews mission operation requirements and Section 8.0 the safety requirements. Section 9.0 gives the experiment status and the future work required to implement the experiment.

2.0 SYSTEM REQUIREMENTS

This section details the scientific requirements for the Combustion of Porous Solids Experiment (COPSE) and also the mid-deck operating constraints. These two areas formed the basis of the subsystems requirements for the experiment.

2.1 SCIENCE REQUIREMENTS

The Particle Cloud Combustion Experiment was originally one of the package of five experiments considered for operation in a combustion facility for operation in Spacelab. The objectives for this experiment are given in Figure 1.1. These objectives were later modified to be accommodated in the mid-deck. The requirements were discussed with Dr. Berlad and revised to be accommodated in a mid-deck experiment. These requirements are divided into:

- Pre-Flight Requirements
- In-Test Requirements
 - Pre-Test Requirements
 - Operating Requirements
 - Post Test Requirements
- Post Flight Requirements

These requirements are given in Figure 2.1. The concentration range and particle type are expanded and are given in Figure 2.2.

These requirements when coupled with the mid-deck constraints form the basis of the concepts detailed in this

ORIGINAL PAGE 19
OF POOR QUALITY

PRE-FLIGHT
REQUIREMENTS

I. EXPERIMENT MATERIAL

- MATERIALS CONSIST OF TUDE, PARYICLES
AND PARTICLE ENVIRONMENT

a. TUDE
LENGTH: 75 ± 0.2 cm MINIMUM
DIAMETER: 5 ± 0.2 cm
IGNITION SECTION: INTERNAL, 0.0 cm
WALL THICKNESS: TBD, cm
WALL CONDITIONING: TBD

b. OXIDIZER
DRY AIR
TYPE: LYCOPODIUM
CELLULOSE
COAL

CONCENTRATION: 10-2000 MG/L
(OF TABLE 21-2)

CONCENTRATION SET POINT: $\pm 5\%$ (SET
POINT NOT
CRITICAL)

STORAGE CONTAINER: AIR TO REMAIN DRY
TEMPERATURE
 $0^\circ\text{C} < T < 50^\circ\text{C}$

PRE-TEST
REQUIREMENTS

II. HOUSEKEEPING REQUIREMENTS

a. PRESSURE

- AMBIENT - UNCONTROLLED
 760 ± 40 TORR AT INITIATION
- STABILITY: ± 1.0 TORR/sec
DURING TEST

b. TEMPERATURE

- AMBIENT $25^\circ \pm 5^\circ\text{C}$
- UNIFORMITY: 1°C TORR/sec
- STABILITY: $2^\circ\text{C}/\text{min}$

c. G LEVEL

- $< 10^{-4}$ G (3 AXIS)
- $\pm 1 \times 10^{-4}$ G

III. TEST CONTAINER ENVIRONMENT

EXPERIMENT PERFORMED AT AMBIENT PRESSURE
AND TEMPERATURE

a. PRESSURE

- SET POINT: 760 ± 40 TORR
(1 ± 0.05 ATM)
- STABILITY: ± 1.0 TORR/sec
(TURNING TEST)

b. TEMPERATURE

- SET POINT: AMBIENT ± 0.5 K
- UNIFORMITY: 1 K/TUBE LENGTH
- STABILITY: 2 K/MIN

c. G LEVEL

- SET POINT: $< 5 \times 10^{-4}$ G
- STABILITY: $\pm 1 \times 10^{-4}$ G

d. PARTICLE CONCENTRATION UNIFORMITY
 $\pm 5\%$ OVER TUBE LENGTH

e. AIR COMPOSITION

- $21\% \text{O}_2 \pm 1\%$
- $79\% \text{N}_2$

IV. TEST READINESS VERIFICATION

THE CONDITIONS ARE TO BE VERIFIED AND
RECORDED PRIOR TO EACH TEST

a. TURBULENCE DECAY

PROVIDE TBD SEC

b. CONCENTRATION

$< 5\%$ VARIANCE

c. PRESSURE

14.7 psi

d. TEMPERATURE

AMBIENT

e. G LEVEL

WITHIN SET POINT

FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

COMBUSTION OF POROUS
SOLIDS EXPERIMENT
SCIENCE REQUIREMENTS

POST FLIGHT
REQUIREMENTS

IN-FLIGHT
REQUIREMENTS

- VII. POST FLIGHT REQUIREMENTS
- a. ALL TUBES TO BE RETURNED FOR ANALYSIS
 - b. STORAGE TEMPERATURE
 $0^{\circ}\text{C} < T < 60^{\circ}\text{C}$
 - c. DATA
ALL DATA AVAILABLE POST FLIGHT

OPERATING
REQUIREMENTS

POST TEST
REQUIREMENTS

- TEST READINESS VERIFICATION
- CONDITIONS ARE TO BE VERIFIED AND
ORDERED PRIOR TO EACH TEST
- TURBULENCE DECAY
PROVIDE TBD SEC
 - CONCENTRATION
<5% VARIANCE
 - PRESSURE
14.7 psi
 - TEMPERATURE
AMBIENT
 - G LEVEL
WITHIN SET POINT

- V. TEST INITIATION AND DATA ACQUISITION
REQUIREMENTS
- a. IGNITION SOURCE
ENERGY SUPPLIED: TBD
TYPE: COIL
REPEAT RATE: TBD
 - b. MATERIAL
(PARTICLES AND GAS - NO ACTIVE
CONTROL)
 - c. SCIENTIFIC MEASUREMENTS
 - FLAME SPEED: 6-100 cm/sec
 - ACCURACY: ± 1 cm/sec
 - FLAME SHAPE: (± 1 mm RESOLUTION)
 - DEFLAGRATION WAVE PROFILE
 - TIME ± 1 sec
 - IGNITION VISUALIZATION
 - EXPERIMENT PRESSURE
 - d. DATA COLLECTION
 - ALL DATA TO BE RECORDED
 - NO REAL-TIME DATA REQUIRED
 - RATE - 100/sec
 - e. HOUSEKEEPING REQUIREMENTS
 - AMBIENT PRESSURE
 - AMBIENT TEMPERATURE
 - G LEVEL
 - RATE: 1 sec
 - f. DISPLAY
 - EXPERIMENT ON SIGNAL
 - EXPERIMENT COMPLETE SIGNAL
 - g. PRESSURE
 - INTERNAL CONTAINER PRESSURE
MAINTAINED AT 1 ATM

- VI. POST TEST VERIFICATION
- TERMINATION OF TEST AND PREPARATION
OF NEXT RUN
- a. VISUAL VERIFICATION
FLAME OUT
 - b. MISFIRE PROCEDURE
TBD
 - c. PRODUCTS
CONTAIN ALL PRODUCTS WITHIN
EXPERIMENT VOLUME

2 FOLDOUT FRAME

Figure 2.1 SCIENCE REQUIREMENTS

PAGE 2-2 INTENTIONALLY BLANK

PRECEDING PAGE BLANK NOT FILMED

	Type	Lycopodium powder	Cellulose			Pocahantas Coal				
	nominal size, μ m	30 (natural size)	50 (45-53)*	25 (20-30)**	7.5 (5-10)**	70 (63-75)*	50 (45-53)*	40 (38-45)*	25 (20-30)**	7.5 (5-10)**
Concentration mg/l (two tubes at each condition)	2000					X	X			
	1800							X		
	1600					X	X	X	X	
	1400					X	X	X	X	X
	1200					x	x	x	x	x
	1000					x	x	x	x	x
	800	X	X	X	X	X	X	X	X	X
	600	X	X	X	X	X	X	X	X	X
	400	X	X	X	X	X	X	X	X	X
	300					X***	X	X	X	X
	200	X	X	X	X	X	X	X***	X***	X***
	100	X	X	X	X			X	X	X
	50	X	X	X	X					
	25	X***	X***	X	X					
	10	X	X	X	X					
	5	X	X	X	X					

* Standard Tyler Sieve, ** Precision Sieves, *** Expected Flammability Limit

Figure 2.2 CONCENTRATION RANGE

study.

The test matrix of potential concentrations was developed in consultation with Prof. Berlad and includes the range of desired particle sizes and concentrations. Each particle concentration shall be carried out in duplicate to validate results.

A general plan of experiment operations is included as Figure 2.3. This figure lists the essential steps that are necessary to perform the experiment. These steps derive generally from the requirements in Figure 2.

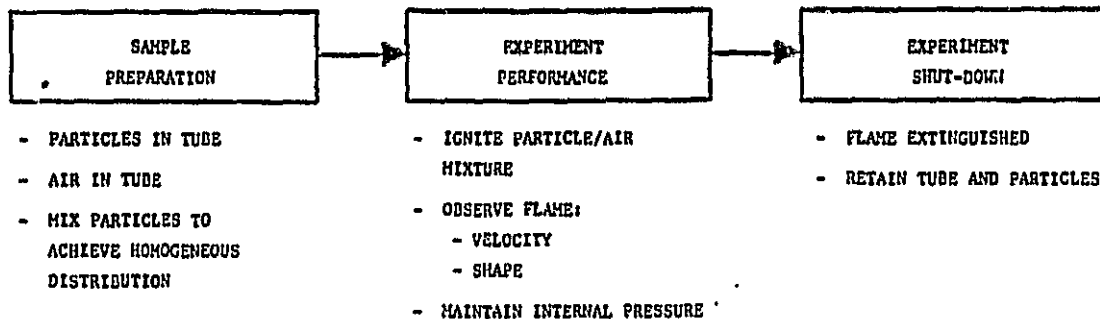


Figure 2.3 EXPERIMENT OPERATION

2.2 MID-DECK ACCOMMODATION

The Combustion of Porous Solids Experiment concept and design is to operate in the mid-deck area of the Shuttle. The experiment hardware should be transferable to the proposed combustion facility with a minimum of modification. The mid-deck has locker areas for experiments. The number of lockers

available for experiments in any flight will depend upon the available space. This in turn depends upon the crew size and mission length. Portions of this area are available for experiment operations. The interfaces for experiments are given in references 3 and 4. The experiments to be performed in the mid-deck will be limited in volume and power consumption, as well as level of crew involvement, for example.

2.2.1 Mid-Deck Experiment Arrangements

The mid-deck area of the STS system is shown in figure 2.4. The location of the lockers is shown in Figure 2.5. There are 33 locker spaces. An experiment can use the lockers themselves, or can utilize the volume of one or more lockers with an experiment-specific structure built around it. An additional area available for experiment operation is located in the galley area.

A summary of the interfaces for each experiment in the mid-deck are given in Table 2.1. The important design parameters are highlighted below.

Structural/Volume The payloads that utilize their own structure must mount to the wire trays of the mid-deck locker region using a single adaptor plate 18.125 inches wide by 10.757 inches high; or through two single adaptor plates to a double adaptor plate 18.125 inches wide by 21.882 inches high. A later development in design released by JSC allows the use of two single plates that are lighter in weight (2.5 lbs.) with the attachment of the structure to four points on these plates. Hardware must extend no further than 20.32 inches from the wire trays including the adaptor plates. Experiments must conform to the defined locker volume. The c.g. of the system is as defined in the Table 2.1.

Thermal/Environment The thermal and the environmental

MID-DECK AREA CONTAINS CREW QUARTERS
AND LOCKER AREA

ORIGINAL PAGE IS
OF POOR QUALITY

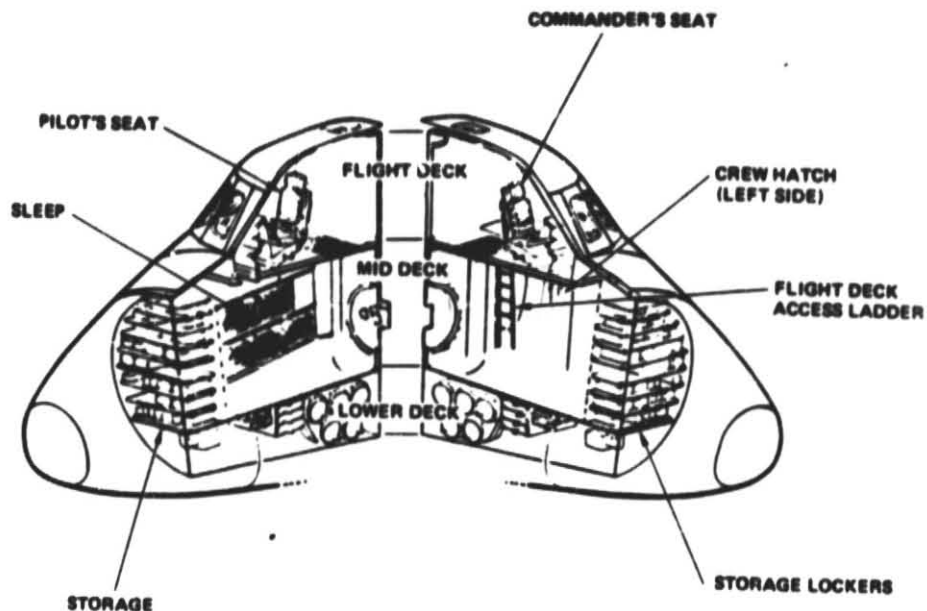


Figure 2.4 MID-DECK LOCATION IN THE SPACE SHUTTLE

MID-DECK HAS TWO LOCKER AREAS
AVAILABLE FOR EXPERIMENTS

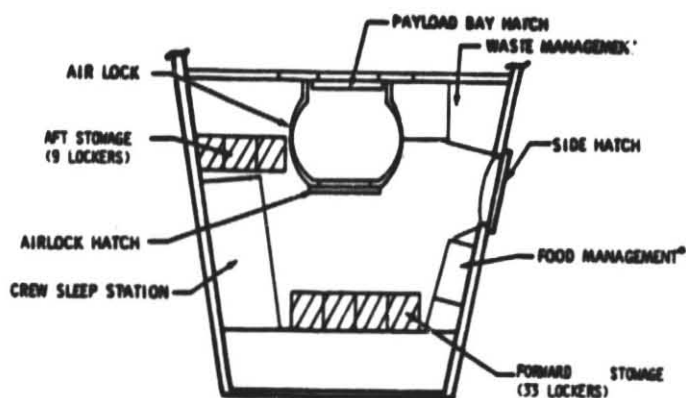


Figure 2.5 MID-DECK AREA ARRANGEMENT

Table 2.1 SHUTTLE MID-DECK ACCOMMODATIONS

I. VOLUME

• Standard Locker Size	9.950" x 17.312" x 20.320" internal dimensions
• Standard Locker Volume	2.00 cubic feet
• Optional Stowage Tray Sizes	
• Large	9.59" x 16.95" x 20.00"
• Small	4.64" x 16.95" x 20.00"
• Single Adaptor Plate Size	10.757" x 18.125" x 0.750"
• Double Adaptor Plate Size	18.125" x 21.882" x 0.875"
• Maximum Total Payload Length	21.062" including adaptor plates
• Maximum Total Payload Width and Breadth	May not extend beyond adaptor plate perimeters

II. MASS

• Maximum Payload Mass	
• Standard Locker	60 lbs. including trays, etc.
• Single Adaptor Plate	69 lbs. including plate, mounting hardware, etc.
• Double Adaptor Plate	120 lbs. including plates, etc.
• Adaptor Plate Mass	
• Single	6.2 lbs.
• Double	12.5 lbs.
• Center of Mass Location	
• Light, centered loads	< 14" from attachment face
• Off-axis or near maximum loads	< 10" from attachment face

III. STRUCTURES

• Steady-State Load Factors	
• Along x-axis	- 3.15 to + 1.22
• Along y-axis	- 0.80 to + 0.80
• Along z-axis	- 1.00 to + 2.50
• Load Factors for Critical or Potentially Hazardous Components	

Table 2.1 (cont.)

• Along x-axis	- 3.3 to + 20.0
• Along y-axis	- 3.3 to + 3.3
• Along z-axis	- 4.4 to + 10.0
• Other Stresses	Random vibrational, acoustic, and transient stresses, as outlined in Interface Control Document

IV. CABIN ENVIRONMENT

• Temperature	
• Normal	68-80 F
• During ascent and reentry	< 95 F
• Air Pressure and Oxygen Content	
• Normal	14.7 PSIA, 25.9% O ₂
• During EVA	10.2 PSIA, 31.0% O ₂
• Emergencies	8.7 PSIA, 32.0% O ₂
• Fixed Rate of Pressure Change	
• EVA Adjustment	2.0 PSIA/min
• Emergencies	9.0 PSIA/min

V. COOLING AND THERMAL

• Passive Cooling	Dissipate heat to mid-deck cabin air
• Preferred Method of Passive Cooling	Fan or equivalent
• Maximum Waste Heat Without Fan	60 watts
• Active Cooling	Dissipates heat via water flow through connectors in mid-deck floor
• Maximum System Coolant Pressure	
• Normal	200 psig
• Safety Factor	300 psig without leaks

Table 2.1 (cont.)

• Payload Surface Temperature	
• Surfaces Accessible to Crew	< 113 F
• Other External Surfaces	< 120 F
• Maximum Total Payload Waste Heat	
• At 14.7 cabin air pressure	
• Two man crew	650 W
• Four man crew	375 W
• At 10.2 PSIA cabin air pressure	
• Two man crew	425 W
• Four man crew	150 W

VI. ELECTRICAL

• DC Power From Orbiter	
• Minimum Voltage	23 VDC
• Maximum Voltage	32 VDC
• Nominal Voltage	28 VDC, all at up to 10 amps
• Maximum DC Continuous Power at Min. Voltage	
• Bus A	224 W
• Bus B	215 W
• Bus C	165 W
• AC Power From Orbiter	
• Frequency	400 Hz, 3 phase
• Minimum Voltage	108 VDC
• Maximum Voltage	120 VDC
• Nominal Voltage	115 VAC, all up to 3 amps/phase
• Connections	Done by crew. Two-wire cords for DC, four-wire cords for AC, with interfaces described in Orbiter specs
• Electrical Bonding Requirements	RF circuits and electrical interafaces shall be electrically bonded to Orbiter structure
• Electrostatic Discharges	Not permitted

Table 2.1 (cont.)

● Alternating Magnetic Fields	< 130 dB above 1 picotesla (30 Hz to 2 kHz) falling 40 dB per decade to 50 kHz, at 1 meter away
● Electrical Interface Noise	
● DC Power from Orbiter	
● Nominal Ripple	< 0.9 volts peak to peak narrowband (30 Hz to 7 kHz), falling to 0.28 volts at 70 kHz, remaining constant to 400 MHz
● During Orbiter Hydraulic Pump Startup (t < 300 msec)	Sawtooth ripple voltage, 4.0 volts peak-to-peak, 500 to 700 Hz, on the 28 VDC power bus
● Transient Spikes	-6 < 300 x 10 ⁻⁶ volt-seconds above or below line voltage. Peak spikes not to exceed +/- 5- volts from nominal bus voltage; rise and fall times < 56 volts/microseconds
● AC Power From Orbiter	
● Nominal Ripple	< 1.5 volts rms narrowband (30 Hz to 1.5 kHz), remaining constant to 400 MHz. Ripple shall not exceed 4% rms of the AC line voltage at inverter harmonic frequencies
● Transient Spikes	Peak spikes not to exceed +/- 600 volts from nominal bus voltage; rise and fall times < 2.5 volts/microsecond

interfaces in the mid-deck are given in Table 2.1. Pressure is as low as 10.2 PSIA during EVA activity. The oxygen partial pressure at 14.7 psi is 25.9%. This partial pressure differs from air; thus combustion validation experiments must include this datum.

The heat rejection by an experiment must be accommodated through coupling to the galley location fluid heat exchanger or through exchange to the cabin air. The fluid heat exchanger is available only at the galley location and thus, use will limit the number of flights available for an experiment. The heat loss must be positively moved to the cabin air if it will be greater than 60 W.

Electrical/Power The total power available to an experiment at a locker location other than the galley is 250 watts. If the power requirements are greater than this, the galley location must be used. The variation in DC power level is 23-32 volts which may require power supplies for equipment power stabilization.

2.3 EXPERIMENT DEVELOPMENT APPROACH

The major constraining factors in the Combustion of Porous Solids Experiment for mid-deck operation are:

- o The number of experiments per flight
- o The length of the tube
- o The number of mid-deck lockers available.

Our approach for developing any experiment for mid-deck is shown in Figure 2.6. The mid-deck operating parameters are identified and compared to the science requirements. The results of this comparison are then used to reevaluate the science

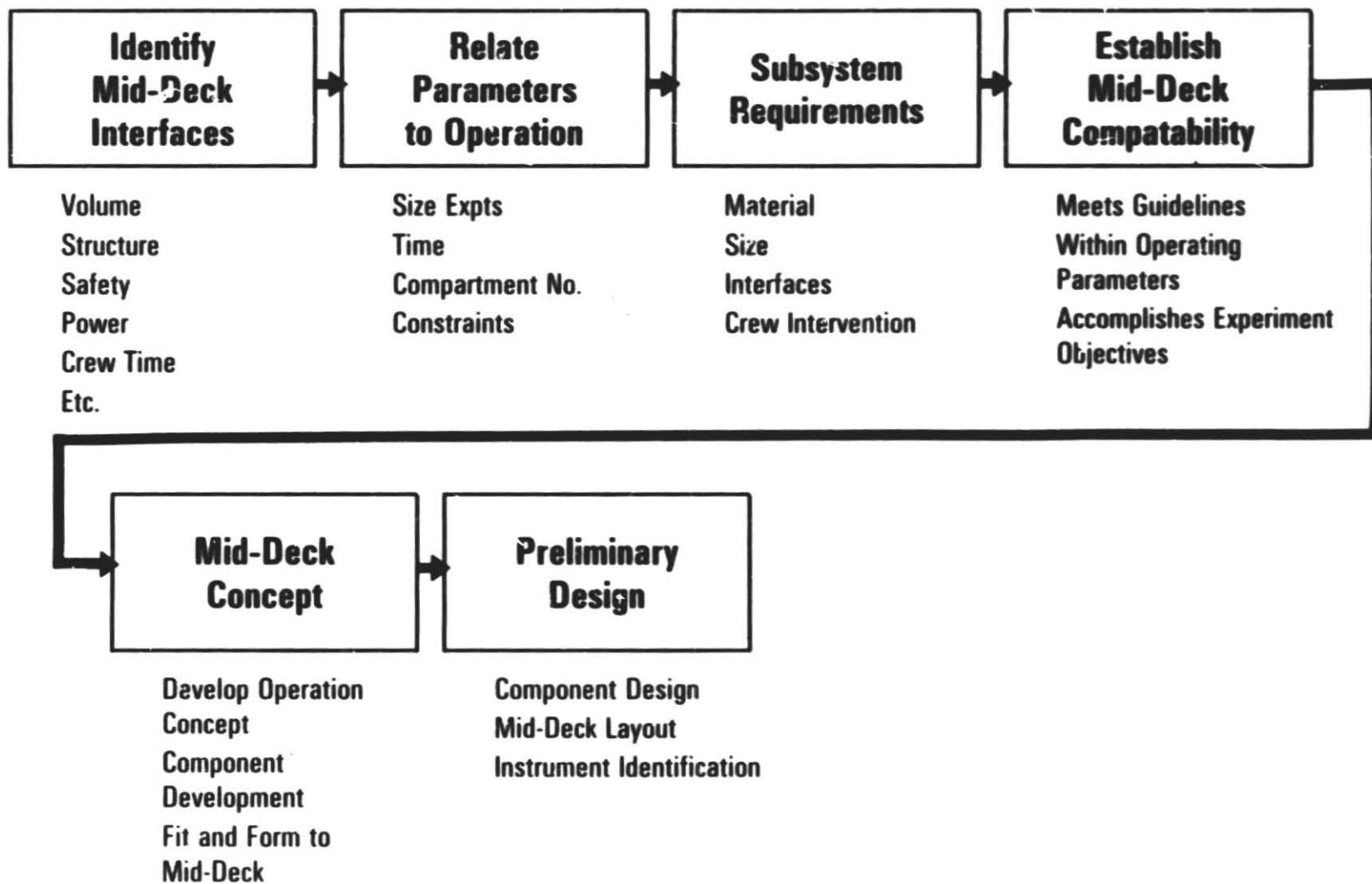


Figure 2.6 MID-DECK DEVELOPMENT THROUGH PRELIMINARY DESIGN

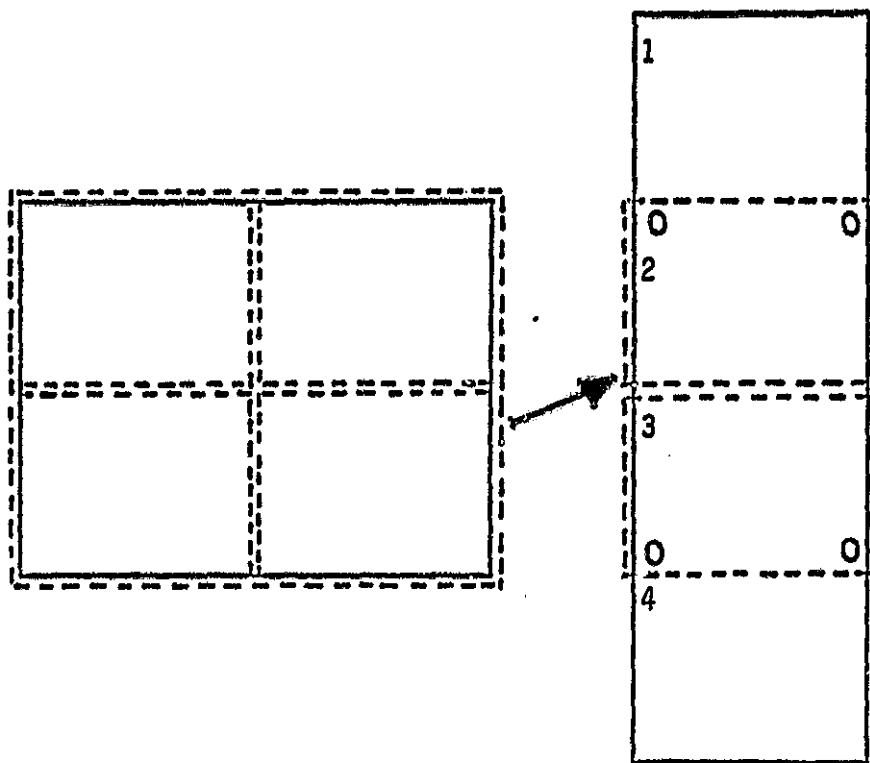
requirements which are then adjusted for mid-deck operation. The subsystem requirements are then derived and these evolve into a mid-deck concept which then evolves into a preliminary design.

The significant scientific constraints are listed in Table 2.2. With these we list two operational considerations. The volume of an experiment is normally one or two lockers. The length of the tubes precludes two lockers and necessitates the use of four locker spaces. The position and mounting methods have changed during the course of this study as the information from JSC arrived.

Table 2.2 INITIAL MID-DECK CONSTRAINTS/CONDITIONS

DESIRED	EXPERIMENT ACCOMMODATIONS
<u>Science</u>	
• Tube - 100 cm	75 cm active length
• Experiment Number -to 100	16 tubes
• Variable FOV for Flame Shape	Fixed FOV at tube center
• Unlimited Film Footage	200'-400' limit
• Pressure Measurement During Experiment	Deleted
<u>OPERATIONAL</u>	
• Mid-Deck Lockers	4 mid-deck lockers
• All Fluids Contained	Individual closed tubes

The original concept was a two by two horizontal locker concept using two double adaptor plates (Figure 2.7a). This



a) 2x2 Locker Two Double
Adaptor Plates

b) 1x4 Lockers Two Single
Adaptor Plates at 2
and 3

Figure 2.7 MID-DECK LOCKER CONFIGURATIONS CONSIDERED

concept was unable to be implemented in the mid-deck and we altered the concept to a one by four vertical concept shown in Figure 2.7b. Later in the design development we learned from JSC (C. Chassay) of an alternate mounting method using two single plates attaching the two outside corners of each plate and carrying the load on the experiment specific structure. This approach utilizes lockers 1 and 4 for overhang with the weight carried from 2 and 3.

The original approach utilized common equipment in so far as possible. The Phase "O" Safety Review at JSC indicated a preference for a closed experiment container that would contain

within its volume all experiment materials. This led to a concept with a number of subsystems or components that were individual to each tube. The decision was made jointly with LeRC to design a "closed" tube system. This necessitated a redesign midway in the contract effort. Table 2.3 shows the impact of design changes.

Table 2.3 COMPARISON OF COMMON & INDIVIDUAL FUNCTIONS IN THE COPSE

COMMON	INITIAL	INDIVIDUAL	FINAL
	VENT		VENT
	IGNITOR CONNECTION		IGNITION CONNECTOR
	INJECTOR GAS		INJECTOR GAS
	HEAT SINK		HEAT SINK
	PRESSURE TRANSDUCER		DATA ACQUISITION
	DATA ACQUISITION	COMMON	MIXER
	MIXER	DELETED	PRESSURE TRANSDUCER

The experiment weight and packaging was estimated twice during the performance period in order to assess mid-deck compatibility. The philosophy was to continue with the experiment concept as defined in the apparatus analysis until either of these parameters indicated that the design exceeded mid-deck accommodations.

The design is carried to a point that allows validation of the closed tube concept; a weight estimate to be made and an ROM cost derived. This design does not incorporate all analyses and mechanisms; some of these will be developed during detailed design.

3.0 APPARATUS ANALYSIS

This section reports the derivation of a concept for the COPSE. The concept is based upon the Science Requirements obtained from Prof. A. Berlad (Section 2.1) and the STS operating constraints. A concept for operating this experiment was derived in the assessment of the combustion facility concept (Ref. 2).

This operation was consistent with science requirements that had been defined by Prof. Berlad. The major thrust in the study of Ref. 2 was to define experiments such that they would be compatible with the Spacelab combustion facility. Another part of that study was to define individually contained experiments that were precursors to combustion experiments that might be carried out later in the facility. This apparatus analysis initially considered operations in the facility. Almost all later segments of the study have been directed toward mid-deck operation.

The apparatus analysis defines an experiment that operates in the mid-deck and that meets significant science objectives. Two major compromises that are necessitated by the mid-deck operation are:

- (1) The length of the tube is 75 cm instead of 100 cm. A tube of 100 cm cannot be accommodated in less than a 5 locker configuration.
- (2) The number of experiments that can be conducted are limited by the available volume.

Other limiting factors include power and heat dissipation. However, these were not deemed to be critical factors in the overall experiment operation.

The initial experiment was characterized by subsystems. The function flow of the experiment is shown in Figure 3.1. These subsystems are summarized in Figure 3.2.

These concepts are developed in the sections below. This development includes comparisons of the various methods considered in the subsystem designs and the basis of selection of a particular design. The final concept is discussed in this final subsection.

3.1 COMBUSTION TUBE

The combustion tube meets the minimum design criteria given in the science requirements (Fig. 2.1). The tube length is 75 cm (29.5 in). The maximum tube inner diameter that is accommodated in this concept is 5.6 cm (2.2 in). Any tube of lesser inner diameter may be used without other modification to the apparatus.

- EXPERIMENT CONTAINER
- EXPERIMENT CONTAINER SUPPORT
- VENT
- PARTICLE DELIVERY
- IGNITION
- INSTRUMENTATION
- ELECTRONICS
- DATA ACQUISITION
- THERMAL CONTROL

Figure 3.2 COMBUSTION OF POROUS SOLIDS
SUBSYSTEMS AND FUNCTIONS

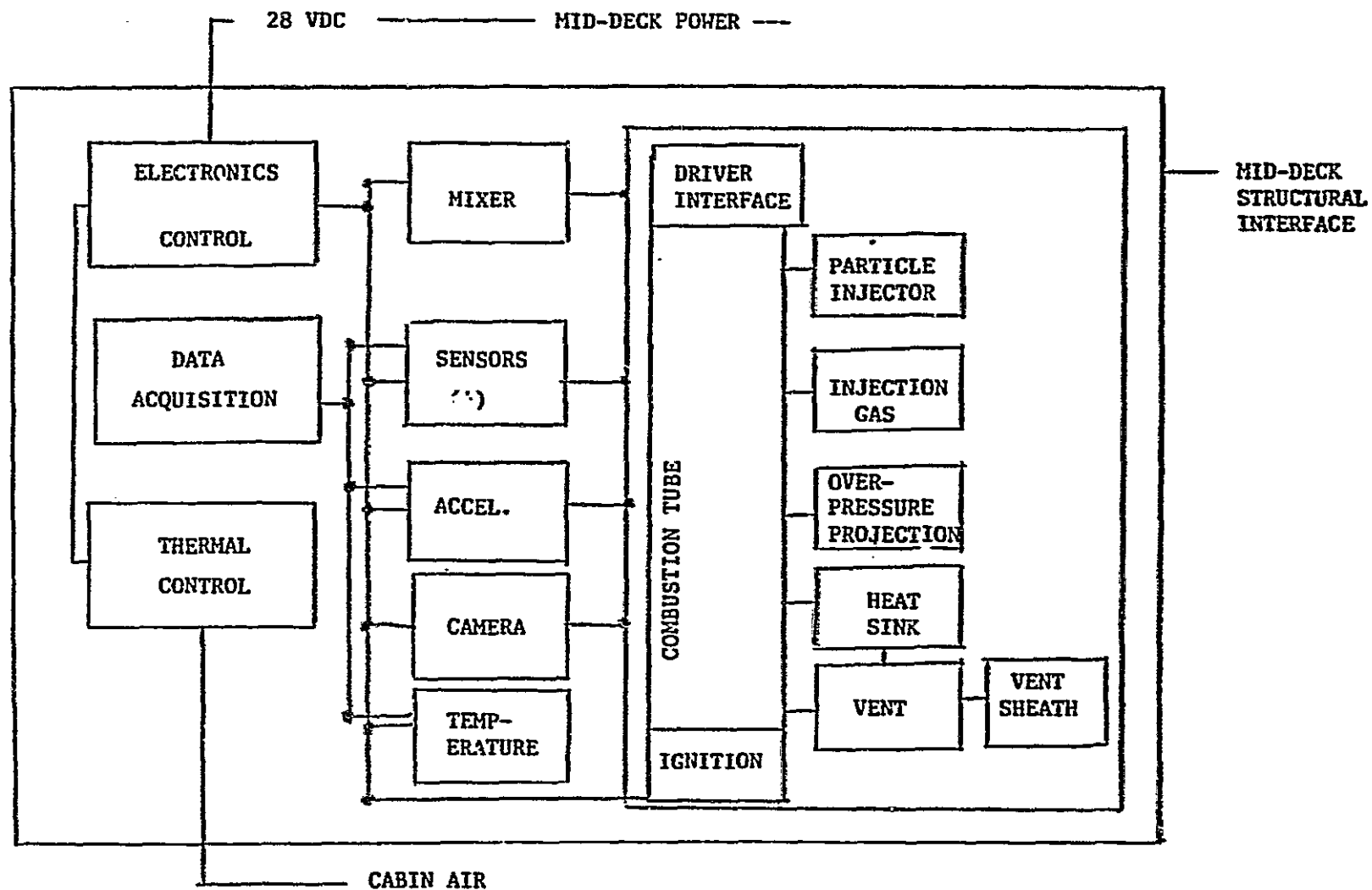


Figure 3.1 COMBUSTION OF POROUS SOLIDS EXPERIMENT - FUNCTION FLOW

3.1.1 Tube Material

Polymethyl methacrylate, borosilicate glass and polycarbonate were considered as candidate tube materials. Table 3.1 summarizes the qualities of these materials relevant to this application. The possibility of shattering led to elimination of glass as a candidate. A clear material is required for visual observation, photography and instrumentation. Of the clear polymers, polycarbonate was chosen because of its fire and shatter resistance. Gold antistatic wall coating and electrostatic techniques to reduce particle/particle and particle/wall adhesion are under investigation by NASA. These materials will reduce the particle adhesion.

3.1.2 Tube Wall Thickness

Three factors were considered in choosing the tube wall thickness. The tube must not rupture during any overpressure which might occur in operation. The deflection of the tube under handling and operational loads must be small enough that no discernable distortion of the flame nor plastic deformation of the material can occur. Finally, the tube must readily absorb the thermal load imposed by combustion as the primary means of cooling combustion product gases. This must be accomplished without significant weakening of the tube. Combination of these considerations which are analyzed below, lead to selection of a 1.25 mm (0.049 in) thickness.

Rupture To ensure the tube will not rupture under pressure, an estimate of the maximum pressure load is made. Should a malfunction of the vent and safety valve occur the tube must not rupture before failure of the vent membrane or of the isolation membrane at the acoustic driver. These are estimated to withstand approximately 51 kPa (7.4 lb/in²). Thus the tube must withstand 101 kPa (14.7 lb/in²) with a safety factor of 2.5

Table 3.1 QUALITIES OF COMBUSTION TUBE CANDIDATE MATERIALS

MATERIAL	ADVANTAGES	DISADVANTAGES
Methyl Methacrylate (plexiglas)	<ul style="list-style-type: none"> • difficult to shatter good transparency Sound deadening high strength per weight 	<ul style="list-style-type: none"> • Low melting point Inflammable Low Thermal conductivity/diffusivity difficult to custom manufacture.
Glass	excellent clarity non-reactive high melting point high thermal conductivity, diffusivity easy to custom manufacture	shatter low hysteresis, not sound damping
Polycarbonate	non inflammable shatterproof good transparency sound deadening high strength per weight	low melting point low thermal conductivity/diffusivity difficult to custom manufacture

yielding an overall safety factor of 5.

$$T = \frac{PD}{\tau}$$

where T is the tensile stress, τ the wall thickness, P the pressure and D the tube (mean) diameter. For polycarbonate $T = 55.1$ MPa (8000 lb/in²), and $P = 101$ kPa (14.7 lb/in²), $D = 5.6$ cm (2.2 in.), thus $\tau = 0.10$ mm (0.004 in.). with the safety factor we have $\tau = 0.25$ mm (0.01 in.).

Deflection Attached at both ends to the apparatus structure, the tube wall sags when subjected to g -forces normal to its axis (e.g. during launch and landing). This deflection, y , is given by

$$y = \frac{5Mgl^3}{384EI}$$

where M is the tube mass, l the length, E the elastic modulus and I the tube moment of inertia given by

$$I = \left(\frac{\pi}{64}\right)(D^4 - d^4)$$

where D is the outer diameter of the tube and

$$\tau = D-d.$$

For $\tau = 0.25$ mm (0.01 in.) at 1 g $y = 0.33$ mm (0.013 in.). Shuttle launch and landing are nominally 3 g. Using a safety factor of 2.5 the calculation is performed for 7.5 g loading. The deflection is then 2.5 mm (0.10 in.), less than 2% of the tube diameter. Sizing for pressure yields adequate thickness for tube rigidity. A calculation of the critical force for column buckling has also been carried out. Under worst case conditions (1 end pinned and the other cantilevered) the tube can support 72 N (16 Lbf)). This failure mode would require collapse of the apparatus structure so that loads would have to be at least an order of magnitude higher.

The handling strength was estimated by assuming the tube is held (as a cantilever) at one end. If the tube were then subjected to extremely rough handling an acceleration of 3 g might be applied. The deflection would then be 25 mm (1.0 in.) at the end with a maximum stress of 6.17 MPa (895 lbf/in²) which is 11% of the yield stress. It is concluded that from structural considerations a wall thickness of 0.25 mm (0.01 in.) is sufficient.

Heat Dissipation The tube wall serves as the single largest sink for the heat released during combustion. It is required that the tube be sufficiently massive to dissipate this heat without approaching its melting temperature of 135 C (275 F). Some of the heat will be carried out of the tube by venting of exhaust gases. To calculate an upper bound on the tube heat loading, this relief mechanism is ignored so that all the heat is absorbed by the tube and the combustion product gas it contains. Further conservatism results from ignoring the role of tube end fittings

and radiative losses in heat dissipation.

The tube volume of 2.05 l contains 0.019 gmole of oxygen at 0.1 MPa (14.7 lb/in²) and 20 C (68 F). If this oxygen is completely consumed in reaction with pure carbon fuel to carbon dioxide, 7450 Joules (7.06 BTU) of heat are released. The temperature rise, T, of the product gas and the tube wall is given by

$$\Delta T = \frac{Q}{\sum_i m_i c_{p_i}}$$

where Q is the heat released, m_i is the mass of species i, c_{p_i} is the specific heat of species i and \sum takes the sum of this product over all i. For the tube wall, $m = 43.4$ g (0.096 lb.) for a wall thickness of 0.25 mm (0.01 in.) and $c_p = 1.26$ J/g C (0.30 BTU/lb F). The carbon dioxide product gas mass is 0.84 g (0.0018 lb) and its specific heat is 0.846 J/g C (0.202 BTU/lb F). The tube wall also contains 2.02 g of nitrogen with a specific heat of 1.04 J/g C. The temperature rise, ΔT , is 130 C (234 F). For a starting temperature of 20 C (68 F), the tube will reach a temperature of 150 C (302 F), 15 C (27 F) above the polycarbonate melting point. By increasing the wall thickness to 1.25 mm (0.05 in), the temperature rise under the worst case conditions is limited to 23 C (49 F) with a final wall temperature of 43 C (109 F). Since the combustion heat release is just sufficient to raise a 0.25 mm thick shell to its melting point, 1.0 mm of wall thickness will remain with its strength unaffected after a combustion test with worst case heat transfer conditions assumed. The 1.25 mm wall thickness is chosen to ensure combustion heating does not compromise wall strength. Although a 1 mm (0.04 in) thickness of the wall will not reach the melting point, the decrease in strength with increasing

temperature of polycarbonate is not well documented. Because of this uncertainty, a safety factor is incorporated into the wall thickness. Thus, the first 25% of the remaining wall is allowed to soften under heating. The remaining 75% is able to sustain all projected mechanical loads with a safety factor of 3. That is, the unsoftened wall thickness is 3 times that required strictly by structural considerations.

3.1.3 Tube Mass

The tube mass is calculated from its dimension and the density of polycarbonate, 1.2 g/cm³ (74.8 lb/ft³). The basic tube wall mass is 219 g (0.482 lb). Allowance for thickening at the end flanges and provision for the particle injection and ignition flanges yields an estimated mass 55% greater, 341 g (0.75 lb).

3.2 COMBUSTION TUBE SUPPORT

Science requirements specify flame propagation tests for coal, cellulose and lycopodium fuels over a range of particle size and concentration (Table 2.2). Multiple combustion tests require use of either a single rechargeable tube or an apparatus with multiple precharged tubes. These two approaches are compared in Table 3.2. Carrying out a large number of tests in a single tube requires thorough cleaning of the tube between each experiment. This will be difficult under zero gravity conditions. It will require considerable operator attention; and most importantly safety concerns over combustion products (gas and solid) which could enter the Shuttle environment make this strategy undesirable. Single precharged tubes that are used for each test solve these problems but require an external storage bin and operator action to mount and dismount tubes. The carousel concept shown in Figure 3.3 addresses these problems.

Tubes are situated around a carousel with instrumentation for 1 active station. The carousel rotates so that tubes enter the active station sequentially. The center of the carousel provides the volume to position all ancillary equipment including the camera, tape recorder and electronics. After a combustion experiment is completed it is rotated again, bringing a fresh tube into the test position. A carousel of 16 tubes is the maximum that can be accommodated in the mid-deck volume selected. Accommodation of more than 16 tests requires changing the 16 tubes originally set in the carousel in a single operation after completion of the first test sequence. About 20 tubes can be stored horizontally in 2 adjacent lockers. The baseline concept and future design is based upon the use of 16 tubes.

Table 3.2 COMPARISON OF SINGLE RECHARGEABLE TUBE
VS MULTIPLE PRECHARGED TUBES

Single Rechargeable Tube	Multiple Precharged Tubes
<u>Advantages</u> <ul style="list-style-type: none"> • Not limited to a design-fixed number of experiments • Simplified experiment design • In flight selection of combustion tests possible 	<u>Advantages</u> <ul style="list-style-type: none"> • No need to clean tubes • Tube Handling minimized • Experiment safety is enhanced • No additional storage space required
<u>Disadvantages</u> <ul style="list-style-type: none"> • Tube must be cleaned between tests • Open tube may cause STS contamination • Cleaning in STS may be cumbersome 	<u>Disadvantages</u> <ul style="list-style-type: none"> • Number of experiments limited to tubes accommodated in experiment space • Adds components to experiment design

ORIGINAL PAGE 13
OF POOR QUALITY

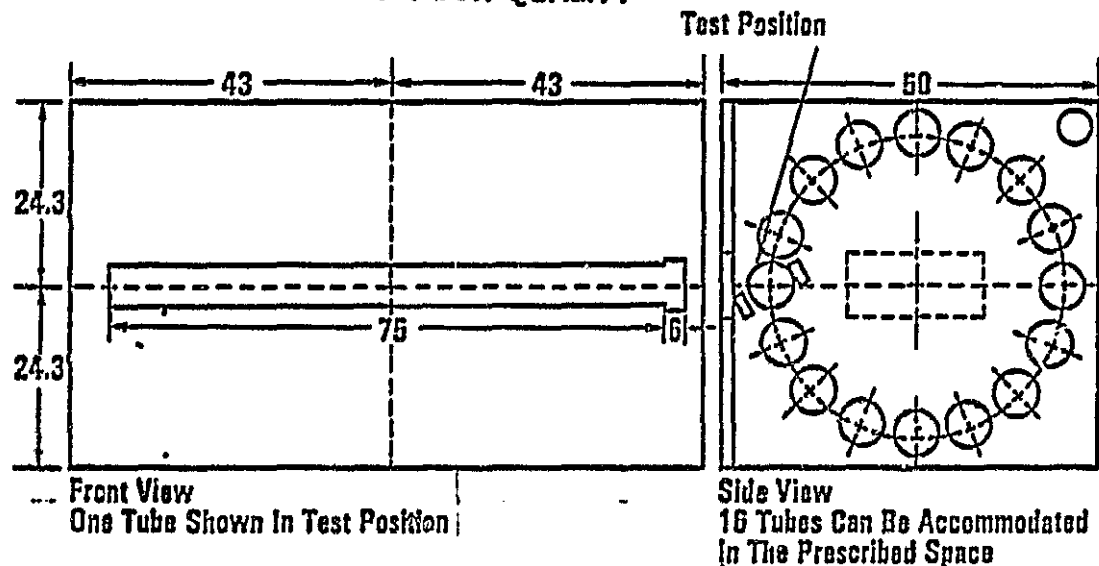


Figure 3.3 COPSE CAROUSEL CONCEPT

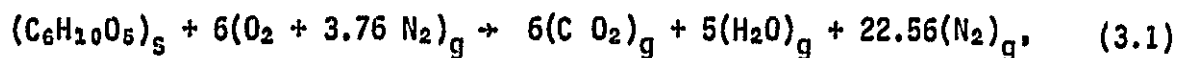
3.3 COMBUSTION PRODUCT VENTING

One scientific requirement is that combustion must occur under isobaric conditions to satisfy the science requirements. With a fixed volume the internal pressure will increase as the gases are heated. Thus a venting system is required.

3.3.1 Venting Requirements

To maintain a constant pressure, any excess gas volume must be vented from the tube. This excess volume can result both from heating and from an increase in the number of moles of gas as the combustion reaction proceeds. For example, during combustion of hydrocarbon fuel (e.g., cellulose and lycopodium) and during incomplete combustion of carbon to carbon monoxide, the number of

moles of product gas is greater than the number of moles of gas reactants. For complete cellulose combustion,



1.175 moles of gas are produced for every mole of gas consumed. For incomplete combustion of carbon,



a product/reactant gas mole ratio of 2 occurs. The heat liberated during combustion which is absorbed by the product gas serves to further increase the final gas volume. The ratio of final to initial volume may be approximated using the perfect gas equation of state,

$$\frac{V_2}{V_1} = \frac{P_1 n_2 T_2}{P_2 n_1 T_1} \quad (3.3)$$

where V is the volume, P is the pressure, n the number of moles of gas and T the gas temperature. Subscripts 1 and 2 refer to the reactant and product states respectively. Since $T_2 > T_1$ due to reaction exothermicity for $P_2 = P_1$ (isobaric conditions) $V_2 > V_1$. Thus a vent system is required which makes additional volume available for the expansion.

3.3.2 Product Gas Volume

Calculation of the product gas volume depends on the type and extent of reaction considered and the (transient) temperature of the gas as venting is taking place. In the case of cellulose combustion the increase in mole number is totally due to water vapor production. If this water vapor condenses on solid boundaries its contribution to product volume will be negligible. For lycopodium combustion, water condensation may even result in a decrease in the number of moles of gas as the reaction proceeds. Because the excess gas is vented during the combustion process, the gas does not reach the equilibrium temperature calculated in Section 3.1.2. The transient heat conduction correlation of Kreith (Ref. 5) has been applied to the cooling of gas as it flows past the tube wall toward the vent port. The temperature of the gas conducting heat to the wall will be near the peak combustion temperature 1500 C (2700 F). The wall temperature will be raised slightly at the inner surface by conduction. Analysis was carried out for a local gas temperature of 1500 C (2700 F) and wall temperature of 40 C (104 F). For hot gas traveling at the flame speed of 1 m/s, the heat transfer coefficient is 39 W/m²C. During the combustion period 1300 J are transferred to the wall. For a flame speed of 0.1 m/s, 7300 J are transferred to the wall. These heat losses lower the gas temperature to the range 75 C (167 F) to 1000 C (1800 F). A further uncertainty is introduced by difficulty in estimating the extent of combustion. This factor will serve to decrease the gas temperatures, lowering the upper limit as much as 500 C (900 F).

The range of uncertainty in V_2/V_1 is the product of the temperature and mole number uncertainties. The minimum gas temperature is 100 C, with a minimum $n_2 = 0.93 n_1$, thus

$$\left(\frac{V_2}{V_1}\right)_{\min} = 0.93 \frac{400K}{300K} = 1.24$$

The complete reaction yields a mole ratio

$$\left(\frac{n_2}{n_1}\right)_{\text{gas}} = 5.41$$

Then for $T_2 = 600 \text{ C}$

$$\left(\frac{V_2}{V_1}\right)_{\max} = 5.41 \times \frac{873K}{300K} = 15.7$$

The rapid increase in wall heat transfer with increasing gas temperature makes it unlikely that such a hot exhaust will be present. For vent sizing calculations, an intermediate value of $V_2/V_1 = 1.44$ is chosen. The mole ratio, n_2/n_1 , is unity as water condensation and incomplete combustion will likely offset the small theoretical increases in mole number by reactions. These figures imply an exhaust gas temperature of 160 C (320 F).

3.3.3 Vent Systems

All vent systems must prevent pressure rise in the combustion tube during combustion by exhausting excess vapor without allowing toxic gases to enter the STS environment. The

vent systems considered may all be classified as either open or closed systems. The specific concepts considered in these two categories are listed in Table 3.3 with their basic advantages and disadvantages. Figure 3.4 illustrates three of the most promising designs. An inflatable bag (Fig. 3.4a) may be attached to the base of each tube. Initially collapsed flat against the tube base, the bag expands to accommodate increases in gas volume. Use of an evacuated chamber as a sink for excess gas is shown in Figure 3.4b. A pressure regulator allows gas to flow from the tube to the chamber whenever test cell pressure rises above its pre-ignition level. Figure 3.4c shows an open container with gas scrubbing agents. The gas is first cooled by passing through a porous metal plate, then scrubbed of toxic gases in a bed of filtering and catalytic agents.

Open Vent System (Scrubber) The most promising open vent scheme uses a gas purification stack. Product gas from the combustion tube flows through the stack and exhausts to the Shuttle atmosphere only after several stages of filtering and scrubbing. Selection of appropriate types and quantities of filtering materials depends on the expected exhaust constituents. Since coal contains the greatest range of chemical constituents, combustion of a fuel-rich Pocahontas coal charge was considered for analysis. We assume the oxygen available reacts with competing fuel elements in direct proportion to their concentration in the coal. The highest anticipated fuel loading of coal is 2 g/l. For a worst case calculation the scrubber cleans the exhaust of 16 tubes, each with a volume of 2050 cm³. Thus the reactant is 65.6 g of coal which is composed of 3.54 g ash, 0.52 g sulphur, 3.02 g hydrogen, 54.58 g carbon, 0.85 g nitrogen, and 3.08 g oxygen. The exhaust will consist of 0.47 g sulphur, 3.54 g ash, 12.8 carbon monoxide, 0.94 g SO₂, 2.0 g H₂O (vapor), and 31.1 g N₂. Additional tar and smoke containing 49.1 g carbon, 2.7 g oxygen and 2.8 g hydrogen will be generated. The heat released is 8.18×10^4 J (77.5 BTU) and the product temperature will be 616 C (1141 F) assuming no heat loss to the

Table 3.3 VENT SYSTEMS

Vent Type	Concept	Advantages	Disadvantages
<u>Open System</u>	Scrubber	<ul style="list-style-type: none"> • Accomodate large gas volume 	<ul style="list-style-type: none"> • Not compatible with closed tube concept • Tubes must be linked to central stack • Effectiveness difficult to measure
	Diffusive	<ul style="list-style-type: none"> • Easily constructed and tested 	<ul style="list-style-type: none"> • Same as scrubber • Must be sealed at conclusion of experiment
	Piston	<ul style="list-style-type: none"> • Mechanical barrier between STS environment and exhaust gases 	<ul style="list-style-type: none"> • Same as scrubber • Volume limited
<u>Closed System</u>	Inflatable bag	<ul style="list-style-type: none"> • Permits totally closed individual tubes • Easy to construct and test 	<ul style="list-style-type: none"> • Volume limited • Barrier material must be protected from rupture
	Vacuum	<ul style="list-style-type: none"> • Solid barrier provided by gas bottle • Very small pressure rises may be achieved 	<ul style="list-style-type: none"> • Most complicated to build: • Not compatible with closed tube concept • Poor sealing of solenoid valve will destroy reservoir operation

OBJECTIVE: Adequacy of tube venting technique

APPROACH: Combustion experiment at 1-G to determine venting requirements

INPUT & VARIABLES:

- (1) fuel details (amount, heating value)
- (2) venting technique

- inflated bag with an upstream heat sink porous disk
- back pressure regulator with a downstream heat sink
- porous heat sink with a scrubber

OUTPUT: (1) tube pressure variation for different venting schemes

HARDWARE REQUIRED:

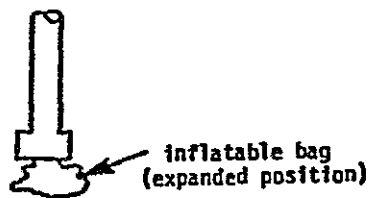
- (1) Flammability tube
- (2) fuel material (need not be solid)
- (3) venting device
- (4) instrumentation

TECHNIQUE: Scheme 1: Inflatable Bag

advantage: (1) self contained experiment does not need external venting
(2) bag can be folded back to save space

disadvantage: (1) requires effective cooling of gas
(2) pressure drop across cooling element
(3) cleared expansion volume is needed

SCHEMATIC:



Scheme 2: Back Pressure Regulator

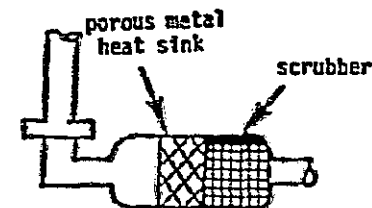
(1) good pressure control

- (1) extra volume for vent vessel
- (2) may need STS vent interface
- (3) requires a sensitive and a fast relieve regulator



Scheme 3: Heat Sink & Scrubber

- (1) simple, no venting required
- (2) device is part of the test stand not part of the tube
- (3) Pressure drop



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 3.4 VENTING CONCEPTS

walls. The actual exhaust temperature expected would be about 100 C (see Section 3.1).

The maximum possible mass flow rate through the vent is calculated assuming the gas exits without significant cooling. From equation 3.3, 115 l of gas will be generated of which 32.8 l remains in the 16 tubes, thus, 82 l is exhausted. For each firing $82/16 = 5.4$ l is exhausted. This volume will include 0.685 g CO which will be reacted to CO₂ in a catalyst. Typically, two times the stoichiometric O₂ flow must be supplied to the catalyst which is accomplished by introduction of 2.85 l of air. The most rapid combustion expected could take place in a period of 1 second. Thus, we expect a total flow rate (air + exhaust) of 8.2 liter/second. A commercial catalyst (Hopkalite supplied by Mine Safety Appliances Inc.) is available for which an exposure time of 0.25 to 0.50 seconds is recommended. A catalyst bed of 13 cm diameter and 32 cm depth yields an exposure of 0.5 s at a pressure drop of 1.8 kPa (0.26 lb/in²).

Besides catalysis of CO to CO₂ the scrubber must filter out smoke particles (soot) and SO₂. Since activated charcoal is itself flammable it was not recommended. Instead, borosilicate glass wool is used as a filter of particles and absorbant for SO₂. A molecular sieve is placed between the glass wool and the hopkalite to prevent water vapor poisoning of the catalyst.

The low back pressure and long exposure times required of the catalyst require construction of a single vent stack rather than provision for a scrubber for each tube. Figure 3.5 shows the proposed vent system in place in the locker volume.

Other open system concepts are shown in Figure 3.6. They all operate by allowing the exhaust products to fill a volume by forcing ambient air out of that colume. In sketch A, a physical piston separates the combustion products from the ambient air. Sketches B, C and D show designs employing a diffusive barrier.

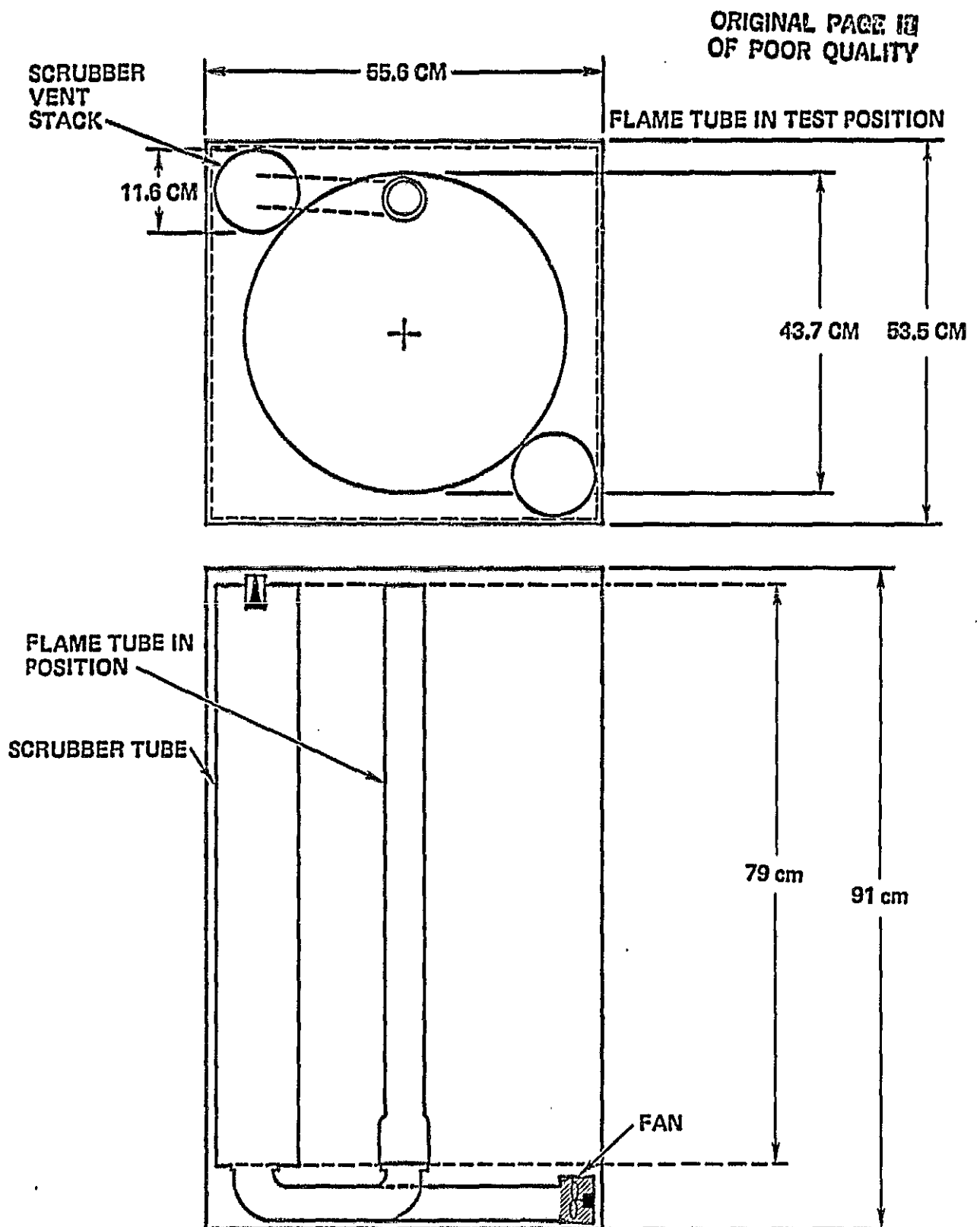


Figure 3.5 OPEN SCRUBBER CONCEPT

The very low rate of molecular diffusion across a long pack isolates the exhaust from the cabin air. The total volume of these reservoirs need not be large as the gas within them will cool to ambient temperatures between tests and the volume of ambient air displaced by the end of the experiment may be negligible. A tube similar to that of the scrubber (Figure 3.4) would be sufficient.

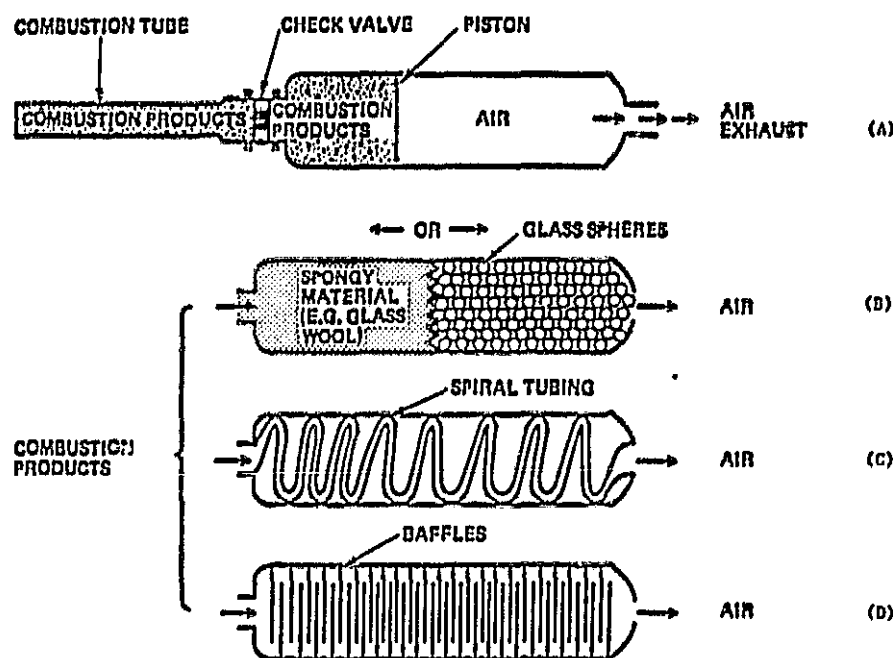


Figure 3.6 TYPICAL OPEN VENT CONCEPT

Closed Vent Systems Both closed vent systems of Table 3.3 were considered in detail. The vacuum system is composed of a chamber connected to the combustion tube under test through a valve. When the tube pressure rises over a predetermined value, the valve opens allowing some product gas to leave the combustion tube and enter the plenum. In principle, this concept provides maintenance of a test pressure very close to ambient through precise operation of the regulating valve. Design and construction of an electrical or mechanical feedback system to

ORIGINAL PAGE IS
OF POOR QUALITY

control test pressure can introduce considerable design complications. The regulating valve must be capable of modulation over a bandwidth of 5-50 Hz, with rapid opening and a leak-tight seal on closing. No valve capable of the projected flow rates, modulation rate and seal was found in preliminary inquiries to manufacturers.

The vacuum chamber itself must be large enough to accommodate the projected gas flow. The calculations presented earlier for fuel-rich coal combustion indicate 82.3 liters of excess vapor are evolved from 16 combustion tests. Cooling of the gas will lower this volume to a about 32 l. In order to apply a partial vacuum to the vent line to overcome heat losses, the reservoir must be of roughly 36 l capacity. A cylinder of 36 l capacity and length 100 cm (39.4 in) (the length available in the locker area housing the experiment) has a diameter of 21.4 cm (8.4 in). Allowing 8 cm (3.1 in) for the vacuum tube's tapered ends and fittings and for a wall thickness of 3.2 mm (1/8 in), the overall reservoir diameter is 23.0 cm (9.1 in).

Fitting this large component and its associated valves and piping in the proposed 16 tube design is difficult. Each reservoir has a mass (if fabricated of aluminum) of 6.9 kg (15.2 lb). It is impractical to provide an individual vacuum system for each tube due to the system complexity. Thus a fully closed design in which each tube is permanently sealed from its surroundings cannot be achieved with this design.

3.3.4 Vent Concept

The closed vent system chosen in our concept employs a flexible membrane. The membrane is of mylar with vacuum deposited aluminum. As vapor is generated during test the developing pressure rise drives gas into the bladder inflating it. The porous metal heat sink originally proposed for the

scrubber will be used in this design to lower the temperature of the exhaust gas and keep fuel particles from entering the vent. Cooling the exhaust gas in this way will lower the exhaust gas volume ensuring the gas bag volume will be sufficient. It will also prevent exposure of the gas bag to hot exhaust gases. This provision is an additional safety feature. Previous analyses indicate an exhaust temperature of 160 C (320 F). Common sealing techniques employed for spacecraft application of mylar with aluminum are used at temperatures above 190 C (375 F). By choosing a pore size as small as the smallest particles (10 μ m, 0.0004 in), smoldering fuel is prevented from entering the vent. Heat dissipation from the exhaust gas through the plate must occur during the combustion transient of 0.1 to 1.0 seconds duration. Passage of the exhaust gas through these pores increases the rate of heat transfer and is further a benefit of the porous plate concept. The width of the plate is chosen by a trade between increased heat capacity and increasing pressure drop as it is made thicker. The material for the plate should have as high a thermal conductivity and diffusivity as possible. Nickel was chosen on this basis among the materials available commercially.

Analysis of the flow and heat transfer characteristics of such a plate is presented in Appendix 1. The results indicate that to make a significant contribution to gas cooling the nickel provided would have to have a mass comparable to the other heat sinks already available; the gas itself and the tube. For example, the 4 g (0.009 lb) of exhaust products expected within a tube have the same heat capacity as 9 g (0.020 lb) of nickel. Further, to limit pressure rise a maximum of 1 cm width of sintered plate is recommended. The plate mass is 30 g (0.066 lb). It will be capable of lowering exhaust temperature from 245 C (473 F) to 176 C (349 F) in the case of fuel rich coal combustion. The filter mass for 16 tubes is 480 g (1.06 lb). If more mass is available for use in the filters, a larger pore size material (100 μ m, 0.004 in) may be sandwiched to the 1 cm plate.

This will further cool the exhaust gases.

3.4 PARTICLE INTRODUCTION

The experiment requires that a predetermined mass of particles are introduced into the experiment container. The particle charge can not be introduced to the combustion tube before flight because

- The particles may form an inflammable cloud which may be ignited accidentally during handling or storage.
- During storage or lift-off particles can become lodged in the vent or its porous filter where they will interfere with proper vent operation.
- Particles lodged in the vent filter and corners will not participate in combustion, altering the effective tube stoichiometry.

A concept is required which vigorously injects fuel particles, dispersing them throughout the combustion tube volume. The injector initially contains the particle charges in a length of tube between two diaphragms. The free volume of this cartridge is filled with dry nitrogen to prevent spontaneous combustion and to keep the particles dry. Particles in the cartridge are injected by applying pressurized air to the diaphragms. By using an elastically flexible diaphragm material such as teflon, the applied pressure will distribute between the diaphragm. When one of the diaphragms bursts the other will suddenly bear the entire pressure and will in turn rupture. The overall volume of pressurized gas will drive the particles into the tube, mixing as a turbulent jet with the stagnant air in the tube. This mixing provides an initial particle distribution throughout the test volume.

An analysis of the volume required to store a particle charge was carried out to size this chamber. Spherical particles will pack into a cube with a volume ratio V , of

$$V = \frac{4/3\pi r^3}{(2r)^3} = \frac{\pi}{6} \quad (3.4)$$

(r is the particle radius and the cube edge half-length). The maximum particle loading stated in the scientific requirements results in a load of 4.10 g. The density of coal is 1.34 g/cm³, thus 3.05 cm³ of coal are required. At optimal sphere packing, equation 3.4 implies that 5.82 cm³ of storage are required. To allow more dilute packing, we chose a volume of 8 cm³ are required. A tube of 1/2 in O.D. and wall thickness 0.041 in (1.04 mm) has a volume of 0.89 cm³/cm. A length of 9.0 cm (3.6 in) between diaphragms is sufficient to house the maximum particle load anticipated. The particle cartridge is shown schematically in Figure 3.7. A total volume of air equivalent to 5-10 cartridge volumes will be required to purge all particles, thus 45-90 cm³ of air will be used. Introduction of this air will result in an equal amount of air entering the combustion vent, imposing a small additional burden on the vent system. The injection system requires storage of a sufficient volume of air to flush 16 cannisters at a pressure sufficient to rupture the diaphragms. An analysis was performed to compare the desirability of storage of this compressed air in individual bottles for each tube versus in one larger bottle for all the tubes. This analysis is presented in Appendix 2. The figure of merit of importance to system safety is the "stored energy" of the compressed air. This is defined as the amount of work the air is capable of performing, if expanded isentropically against the ambient pressure. From this viewpoint, small individual

bottles are preferred. If each unit is self-contained, it requires only an electrical line to be carried to each injection valve from the central controller. A single air supply requires multiple compressed air lines which would emanate from a multiple position valve or from a rotating seal. Routing of these lines would be further complicated by the need to accommodate the rotating carousel. The individual system requires no pressure regulation, further reducing the number of parts and the complexity. On this basis, a design using individual compressed air bottles for each injector is used.

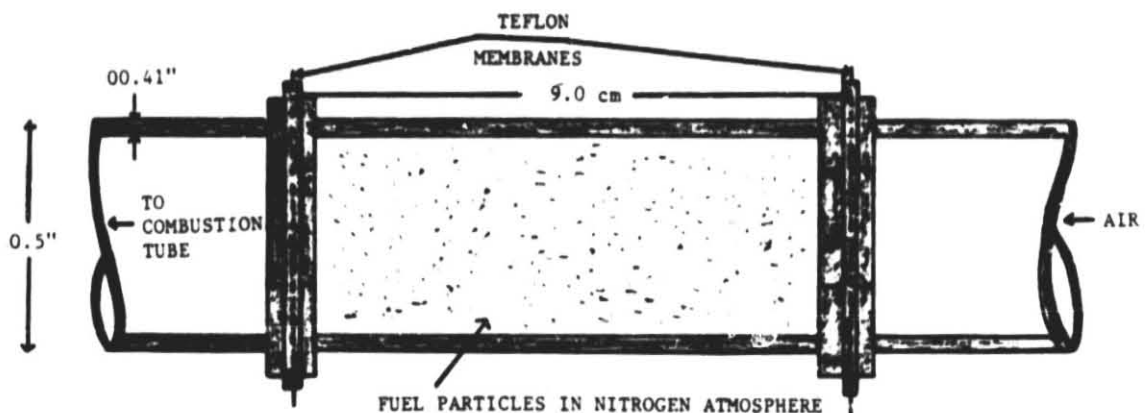


Figure 3.7 FUEL INJECTOR SYSTEM

3.5 PARTICLE MIXING

The injector system will not provide the homogeneous distribution of particles necessary to meet the scientific requirements. An additional mixing system must be provided. The mixing system operates by creating a large scale motion of the particles. Turbulent and diffusive processes complete the mixing at the smaller size scales in which they are efficient. Three mixing schemes were analyzed both in terms of their efficiency and practicability. Figure 3.8 schematically shows a mechanical shaker and an acoustic mixer. Aerodynamic mixing was also

ORIGINAL PAGE IS
OF POOR QUALITY

Particle Dispersion

INPUT & VARIABLES:

- (1) flammability tube geometry (fixed)
- (2) injection tubing geometry
- (3) particle type, size, and loading
- (4) air jet velocity, momentum, duration

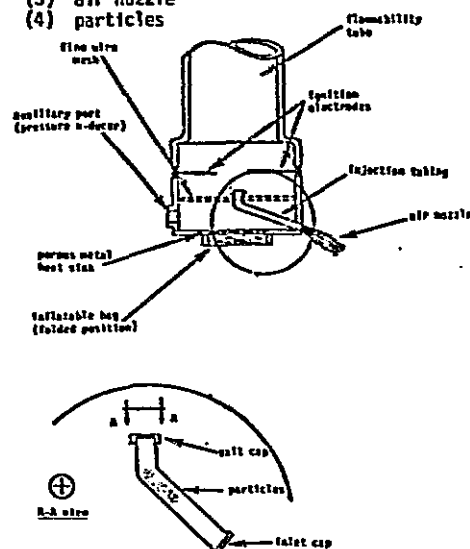
OUTPUT:

- (1) optimization of injection tubing geometry, location and position
- (2) air jet parameters
- (3) interface between air nozzle and injection tubing

HARDWARE & MATERIALS REQUIRED:

- (1) flammability tube
- (2) injection tubings
- (3) air nozzle
- (4) particles

SCHEMATIC:



Scheme a: Mechanical

- (1) mixer motion parameters

- (1) fastest mixing conditions to achieve uniform distribution

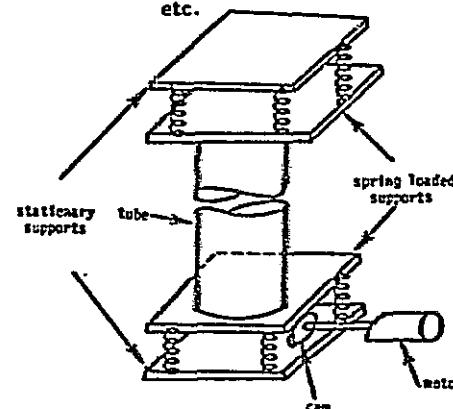
- (1) flammability tube
- (2) particle injection hardware in column (a)
- (3) shaker hardware
- (4) diagnostics: 3 to 4 light sources and detectors

ADVANTAGES:

- (1) proven technique

DISADVANTAGES:

- (1) complex, moving parts, linkages, etc.



Scheme b: Acoustic

- (1) amplitude and frequency of acoustic generator

- (1) optimize sound generator parameters for efficient mixing

- (1) flammability tube
- (2) particle injection hardware
- (3) Piezoelectric transducer, & wave generator
- (4) diagnostics as in column (b)

- (1) simple, no moving parts

- (1) requires "proof of principle"

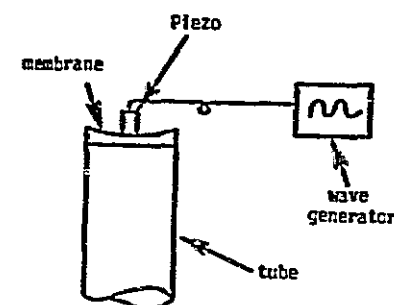


Figure 3.8 COPSE MIXING CONCEPT

considered. This device would resemble the acoustic mixer with the acoustic drive replaced by a motor driven propeller.

3.5.1 Mechanical Mixing

Mechanical mixing involves mounting the tube on flexible or moveable supports which transmit a cyclic motion to the tube and shake the particles inside. The moving tube causes particles on the wall to be moved and possibly thrown from the wall. Particles in the interior volume may be struck by the tube or will be set in motion by the air as it moves. The particles would only oscillate with the tube wall and air in synchronized motion were it not for their slip. The ultimate mixing mechanism is collision between particles which permits their density equilibration as it does for molecules of a gas. The mechanisms of particle collision are: collision with the wall caused by the particles slipping through air (the wall has zero slip); collision with other particles which occurs only because particles of different diameter have different slip velocities (identical particles will move in unison and will not collide); and development of a secondary air flow (superimposed on the one dimensional flow induced by tube wall oscillation) which may initiate recirculating regions. The extent of these effects may be quantified by calculating the motion of particles in an oscillating flow field and counting the fraction of particles which collide with the wall and with each other.

Analyses of the motion of particles in an oscillating flow field, of their mean free path and collision frequency have been carried out and are presented in Appendix 3. The analyses indicate that the shaker would be an inefficient means of mixing particles. Two modes of particle motion were identified which bound mixer design. At higher shaking frequencies, particles will not follow flow fluctuations, their positions remaining relatively fixed in the inertial frame as the tube and air

oscillate. At very low frequencies particles track the flow exactly remaining stationary in the tube (oscillatory) reference frame. In the low frequency limit, no particle/wall collisions will occur while for high frequencies no kinetic energy is transferred to the particles. Particle/particle collisions are only possible if there is a distribution of particle sizes and if the shake frequency is neither the high or low frequency extreme. The frequency of particle collision will likely be low even in this case owing to the relatively large mean free path and small difference in slip distance between particles of similar diameter and density. The frequency band between the two extremes described above is itself a function of particle diameter and density. Thus shaker behavior would have to be tuned for each tube; it is particle and not tube dependent.

The mechanical shaker concept also presents an engineering design problem. The system of cams and motor(s) required results in a complicated mechanical design and requires vibration secure mounting for surrounding hardware. Provision for the tube motion would have to be provided in the carousel which will complicate the carousel design.

3.5.2 Acoustic Mixing

Acoustic mixing operates on the same principle as ultrasonic cleaners. In this concept particles move due to an acoustically driven pressure field. The acoustic driver is coupled to one end of a tube. When it is operated at a resonant frequency of the tube, a stationary acoustic pressure field is developed causing particles in the tube to migrate to pressure minima of the standing wave pattern. Changing the driving frequency to a different tube harmonic causes particles to travel to a new site. If the driving frequency is alternated periodically, the particles are kept constantly in motion. The pressure field is varying both spatially and temporarily and nearby particles do not

receive the same impulse and will collide. Collisions with the walls are likely due to induced pressure gradients. Evidence from ultrasonic cleaner performance is that the acoustic mixer should be very capable of causing wall collisions and of loosening particles adhering to walls or to one another by electrostatic forces. Figure 3.9 shows the proposed mixing concept schematically.

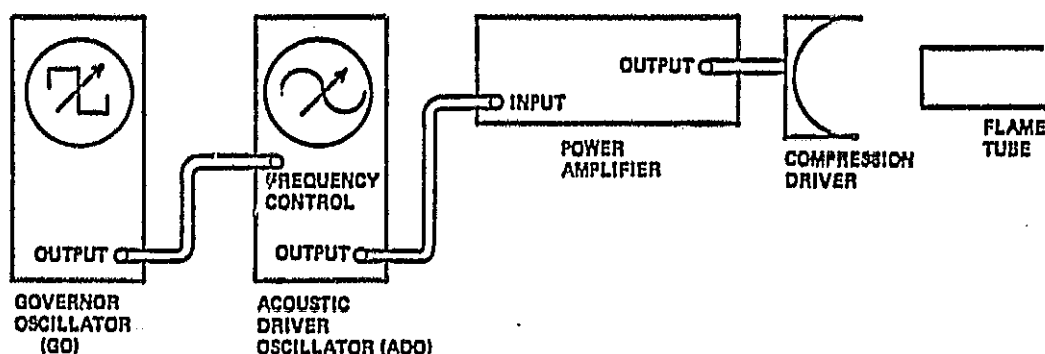


Figure 3.9 ACOUSTIC MIXER DESIGN

The acoustic concept is an uncomplicated engineering design. Further analyses were conducted to size the system. There is no direct method to calculate the minimum power required to mix particles acoustically. Culick (Ref. 6) gives approximate formulae for particle damping. For mixing, the excitation power must equal or exceed damping loss under a particular set of tube conditions. The most severe damping occurs for a high density of small particles driven at high frequency, a worst case of 0.8% particle loading by volume (10 g/l) of 10 μ m diameter particles

oscillating at 30 kHz was considered.

The upper bound on driving frequency of 30 kHz was estimated from the number of modes driven at that frequency. The tube fundamental is at 225 Hz and for a harmonic of order n , $2n + 1$ modes are created. Thus near 30 kHz, 265 modes are present spaced at an interval of 3 mm (0.12 in) along the tube. The largest particles would nearly touch other particles at adjacent modes, blurring the nodal pattern. Higher frequencies would then not contribute to mixing with this technique. The power dissipation for this case is 0.13 watts. An acoustic driver with an efficiency of 0.5% would require 25 watts of driving power to attain the required output level. This drive level is readily available using compact audio equipment.

It is necessary to determine the program of drive signals that are required. Both the resonance frequency for tube drive and the alternation rate between resonances are required. This analysis is presented in Appendix 4. At a lower resonance near 1500 Hz, a switching rate of 1 Hz is possible to another resonance near 1725 Hz. This range of operation is easily attainable with relatively straight forward electronic circuitry and commercially available acoustic drivers.

If an open tube cannot be used, the drive must be separated from the tube; such a separation is also required to prevent particles from entering the driver body. A diaphragm is proposed for covering the tube end. Acoustic losses associated with the diaphragm have been calculated to guide diaphragm material selection. In Appendix 5 it is shown that whereas a 100 μ m aluminum sheet would create a loss of 27 db a 1/2 mil (12.7 μ m) mylar diaphragm with vacuum deposited aluminum will cause only a 1/2 db loss. A double mylar diaphragm has been recommended to isolate the tube and transducer. A double diaphragm creates a particle free zone at the end of the tube so that hot combustion gases will not penetrate the second diaphragm.

Appendix 5 presents an analysis of the acoustic loss likely if a gap exists between the acoustic driver and the tube. It is shown that a gap between the driver and tube of 1 mm (0.04 in) will result in a 10 db loss in sound intensity. To eliminate this loss, an airtight (rubber to rubber or rubber to metal) seal is required between the driver and tube. An acoustic impedance match between the driver horn and the tube should also be provided.

3.5.3 Aerodynamic Mixing

Particles in the size range of 10-2000 μm to be used in the experiment will tend to track the fluid motion. A mixing strategy is to induce a turbulent flow field in the tube. Air and particles the air carries are thoroughly mixed to a very fine scale in such a field. While the tube air is normally stationary, imposition of a free jet would stimulate turbulent mixing. To avoid introducing more air into the tube, a propeller is placed within the tube to create a jet and a wall recirculation zone. A number of design parameters including propeller diameter and angular rate were determined analytically. These calculations are presented in Appendix 6.

The factors addressed in the analysis include the spreading angle of a turbulent jet, provision for a less energetic return flow and elimination of any obstruction which could allow particles to collect and stagnate. This latter provision shall be incorporated into any final mixer design. As a result of this analysis a range of propeller diameter, propeller pitch angle, and rotation rate were specified and a test program was recommended to determine the best configuration within the range. Preliminary tests were successful only for larger diameter propellers mounted outside the tube. Further design work is required to develop a propeller optimized for operation inside

the tube.

3.5.4 Low Gravity Considerations

It is necessary to compare the mixing efficiency of competing concepts under laboratory conditions though their performance is most important at the reduced gravity experienced in orbit. An analysis is performed to relate mixing behavior under these two environments.

All mixers must overcome particle settling to the chamber wall and bottom under gravity. The rate of settling is a function of the gravitational acceleration, g , and the particle density and diameter. In order to properly simulate the settling rates experienced in space ($10^{-4}g$ or less), the particle density and especially particle diameter may be scaled for testing under 1 g . The appropriate scaling law has been derived for the range of g levels which may be encountered aboard the Shuttle. This analysis which encompasses both Stokes and modified Oseen flow regions is presented in Appendix 7. Under $10^{-2}g$ conditions a particle of diameter D behaves like a scaled particle of approximately $D / 15.7$ at 1- g . Thus for example, to simulate low g mixing of 800 μm particles in the laboratory, 51 μm particles should be used.

3.5.5 Conclusions

Three concepts were analyzed:

- The mechanical concept presented a complicated engineering design and is incompatible with the carousel concept.

- Acoustic drivers with power and frequency required to mix particles in the combustion tube do exist. Our analysis shows that this approach will mix the particles.
- The aerodynamic mixing concept using a propeller is simple to implement and analysis indicates that propeller shapes are available that will perform.

The two methods selected for implementation in test hardware were the acoustic mixer and the aerodynamic method. Test results at LeRC and at TRW showed that the propeller concept did not give adequate mixing. The acoustic mixing concept does satisfactorily mix particles. Therefore, the acoustic mixer is the preferred approach.

3.6 IGNITION

Combustion is initiated by forming an ignition kernel at one end of the tube (see 3.1). The requirements of the ignitor are:

- Heating a sufficiently large combustion volume to ensure ignition
- Rapid heating so that the cue for instrumentation start is well defined and for creation of an even flame front
- High reliability.

3.6.1 Spark Discharge

In this concept a pair of electrodes is built into the tube and a high voltage discharge between them used to form the ignition kernel. A 30 kV discharge will deliver a spark of about 1 cm (0.4 in) length. The spark provides virtually instantaneous

local temperature rise but it is fairly thin and the heated volume may be small. An advantage to the spark is that no oxygen is consumed by the ignition system itself so that the chemical stoichiometry within a given tube is not upset. Spark ignition may have electromagnetic interference (EMI) problems associated with it. Safety analysis must also be made to assure that the higher voltages generated present no problem.

To avoid an external electrical connection all the tubes must be connected in advance. The ignition cable has a 0.6 cm (0.25 in) diameter. Wiring two such cables to each of 16 tubes with allowance for carousel rotation will be difficult in the available space.

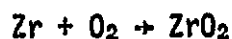
3.6.2 Preflame Ignitor

The other ignitor concept relies on ignition of a small preflame on an intermediate material. The preflame then ignites the particles. Ignitable coatings on wire and metal film combustion have been investigated. Ignitable coatings are less stable and more likely to be accidentally ignited by shock or electrical discharge than metal film. Considerable manufacturing and operational experience has been gained on the application of striated zirconium foil ignition in photoflash application. This technology is chosen for the preflame ignitor owing to its physical stability, safety and dependability and the level of knowledge and experience related to it. Zirconium foil is striated and separated in fine threads which are tangled into a

The zirconium ball is pressed onto two electrodes so that when a low voltage (3-6 V) is placed across the terminal a current of a few hundred milliamps is momentarily induced.

This current resistively heats the zirconium to its ignition temperature. Combustion of the metal is extremely exothermic and rapid, with rise times of about 10 msec. Besides its low voltage and power requirement, the metal combustion

ignition device is attractive as it heats a relatively large volume, increasing the probability of igniting the particle cloud. Since combustion of the zirconium consumes oxygen, the amount of foil used must be limited. If 5% of the oxygen in the tube may be used to burn zirconium, and the reaction is



71 mg of foil may be used under the oxygen constraint. This corresponds to about 3 cm³ of shredded zirconium foil which should be a sufficient kernel volume. Combustion of this quantity of zirconium releases 226 J. This is sufficient to heat the zirconium to 3600 C (6500 F) neglecting dissociation heat loss via radiation and conduction through the electrodes and the surrounding air. It is concluded that the zirconium foil will generate heat sufficient to assure creation of an ignition kernel of ample volume and temperature. Rise time to achieve peak temperature is approximately 10 milliseconds.

A limitation of zirconium combustion is that it allows only a single attempt at ignition. In discussions with the principle investigator, Professor A. Berlad, a single attempt system of this type was considered viable.

3.7 INSTRUMENTATION

Measurement requirements have been related to the instrumentation requirements. The relationships are shown in Table 3.4.

TABLE 3.4 DATA ACQUISITION SYSTEM

REQUIREMENT	METHOD	EQUIPMENT
Monitor particle mixing	optical transmission	4 light sources 4 light detectors *
Flame front observation	photography	high speed camera
Flame propagation rate	local IR detection	IR sensors *
monitor g level		Accelerometer

Data acquisition during combustion is planned via high speed cinematography and flamefront detection with discrete infrared (IR) sensitive detectors. Determination that particle mixing has yielded a homogeneous spatial distribution of particles will be made by transmission measurement using the same detector and light sources paired with each detector.

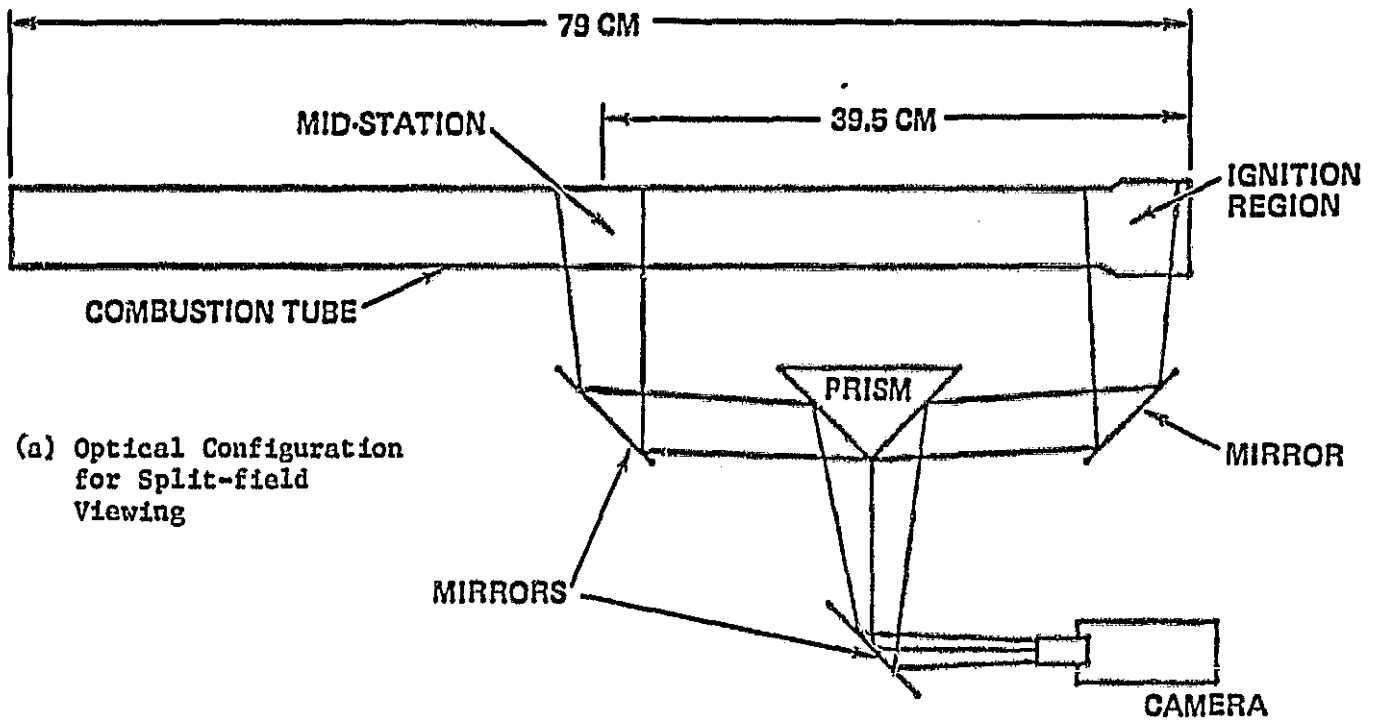
3.7.1 Photography

Design of the photographic system was based on the image resolution, field-of-view and framing rate requirements. Imaging of two discrete regions of the combustion tube will meet the scientific requirements. The camera field-of-view will be divided into halves using a system of mirrors and a prism. One half frame will record events in the vicinity of the ignition

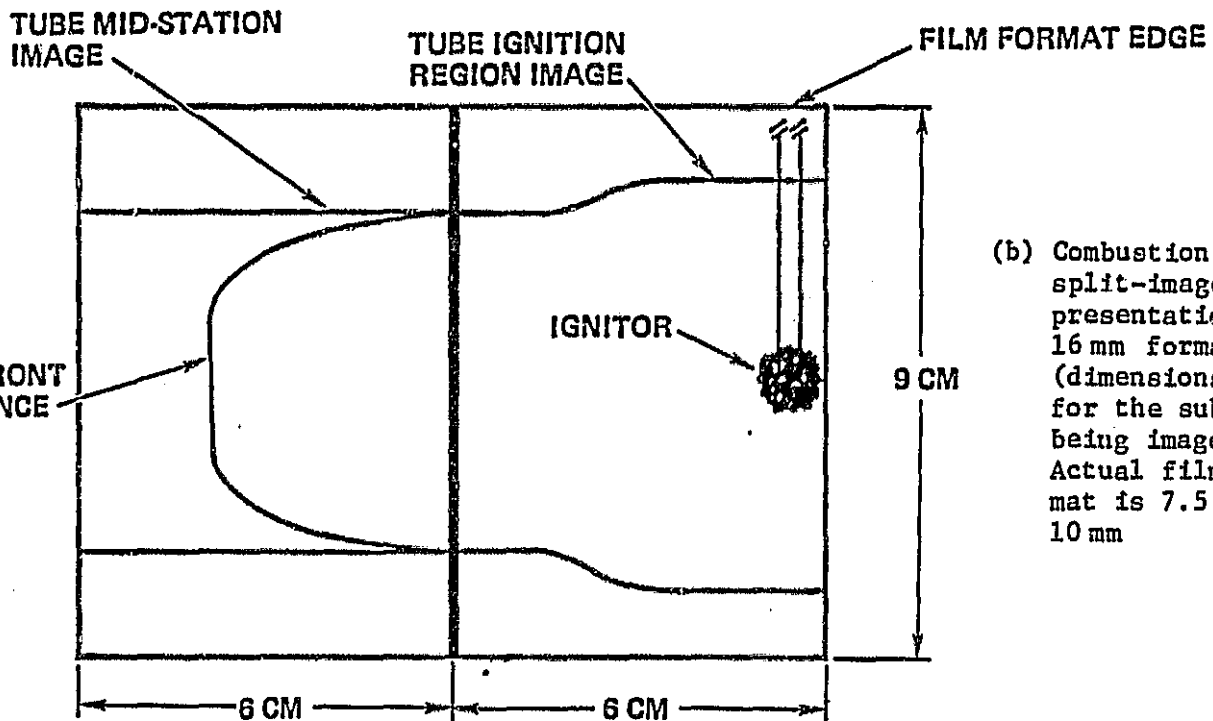
point while the other will record the flamefront passage midway through the test section. For a 16 mm film format the available field-of-view is determined as follows. The 16 mm format has a rectangular recording area of 9 x 7.5 mm (0.35 x 0.30 in). Each half-frame is 4.5 x 7.5 mm (0.18 x 0.30 in). Magnification is chosen such that the tube walls are just visible at the edges of the film, thus 7.5 mm on the film corresponds to 7 cm (2.8 in) on the tube itself. Along the shorter dimension (4.5 mm), a 4.2 cm (1.7 in) length along the tube is visible. The photographic optics configuration and the image is sketched in Figure 3.10.

Once the field-of-view is chosen, selection of the framing rate determines the number of images in which the flame will appear. The flame images will serve both to qualitatively describe the flame structure and to determine the rate of flame propagation. The latter requires a minimum of two consecutive flame images on sequential frames. Additional images would serve to increase the accuracy of the rate measurement. The maximum framing rate is limited by the film capacity of the camera. Because of space and especially mass considerations for the overall experiment a camera with a 200 foot cassette capacity is optimum. By using thinner 2 mil mylar film, this capacity is increased to 225 feet. Each time the camera is started, 1 foot of film is lost as the mechanism accelerates and an additional 1 foot is lost at the end of the run to deceleration. Thus for 16 tubes, 32 of the 225 feet are consumed without data recording, and $(225 - 32)/16 = 12.1$ feet of film remain for each tube. The film is formatted at 40 frames per foot, thus 483 frames are available for each run. A rate of 100 frames/second is thus recommended, allowing 4.8 seconds of data acquisition. The film use budget is shown in Figure 3.11 for each tube. At a maximum expected flame propagation rate of 1 m/s, the flamefront will be within each viewfield for 43 msec. The 100 frames/seconds rate will yield 4 to 5 consecutive flamefront images, satisfying the requirements imposed to calculate propagation rate.

FIGURE 3.7



(a) Optical Configuration
for Split-field
Viewing



(b) Combustion tube
split-image
presentation on
16 mm format
(dimensions are
for the subject
being imaged)
Actual film for-
mat is 7.5 mm x
10 mm

Figure 3.10 OPTICAL SYSTEM CONCEPT

ORIGINAL PAGE 13
OF POOR QUALITY

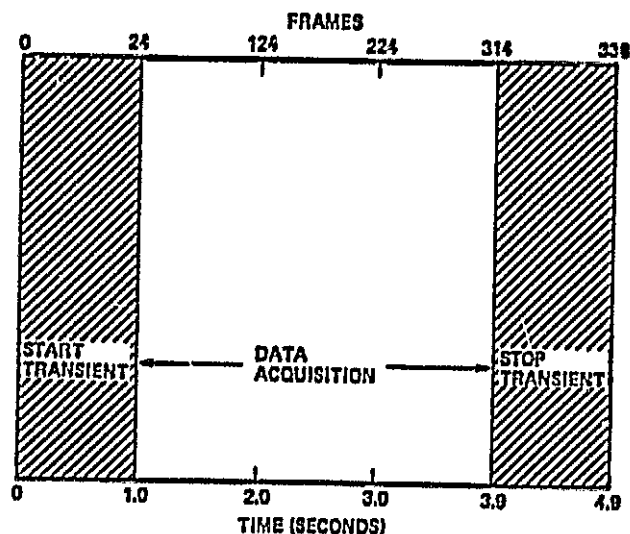


Figure 3.11 FILM USE BUDGET: FILM SPEED = 100 FRAMES/SEC

An image resolution of 0.1 mm is specified in the science requirements. Resolution is determined for this apparatus by film resolution and image magnification. The split screen optical system yields an image size ratio of 9.3/1. The resolution at the experiment scale is thus the film resolution divided by 9.3. The film must have a resolution of 10.8 μm or 9.3 lines/mm. Since optical aberration by tube walls, mirrors and the camera lens combine to diminish resolution, film of 100 lines/mm resolution is required.

At the extreme of very slowly propagating flames, the 4.3 second data acquisition time is sufficiently long to ensure imaging the flame at both the ignition and mid-tube stations. For a 40 cm (15.7 in) separation between the two stations, flames propagating as slowly as 13.8 cm/sec (0.45 feet/sec) will be photographed at both sites.

3.7.2 Particle Homogeneity

Verification that the mixer has succeeded in homogeneously distributing the particles is specified by the scientific requirements of the porous solids combustion experiment. Particle cloud optical density will be measured at four equally spaced stations along the tube length. At each location a sensor is placed directly opposite a collimated light source. Before particles are introduced into the tube, the light intensities are automatically adjusted so that four sensor signals are equal. The particles are injected and mixing carried out until four signals are again equal. The fraction of light which penetrates the particle cloud as a function of particle diameter and population density is computed from Beer's law, which, along with data on the sensor allows calculation of the locus of particle density and diameter which the system can accommodate. This analysis is carried out in Appendix 8. An operating envelope is defined there in the locus of particle size and density. Sensor linearity, measurement resolution and allowance for variation in local population density permit reliable measurement at light transmission levels of 9% to 91% of the empty tube value. This implies that for 10 μm diameter particles, particle clouds of population density from 16 to 415 mg/l may be reliably measured. For 100 μm diameter particles, the population density detection limits are 163 to 4150 mg/l. Figure 3.12 shows the operating range of the detector. A method of interpretation of the sensor output in terms of percent variation of particle density about a mean is also presented in Appendix 8. This analysis also provides a computational algorithm for obtaining these data.

3.7.3 Flamefront Sensing

Discrete sensing of flamefront passage will be used in addition to cinematography in measuring flame propagation rate. Sensors with near infrared sensitivity (0.8 - 2.0 μm wavelength)

are stationed at four fixed locations along the tube. By measuring the time between flame passage at the discrete detector location as detected by the radiation signature, a measure of flame velocity is obtained. By using light sources for the homogeneity detector rich in IR radiation (e.g., incandescent bulbs), the flame and homogeneity detector functions can be fulfilled by the same detectors. Use of IR detectors will also reduce interference from external light sources.

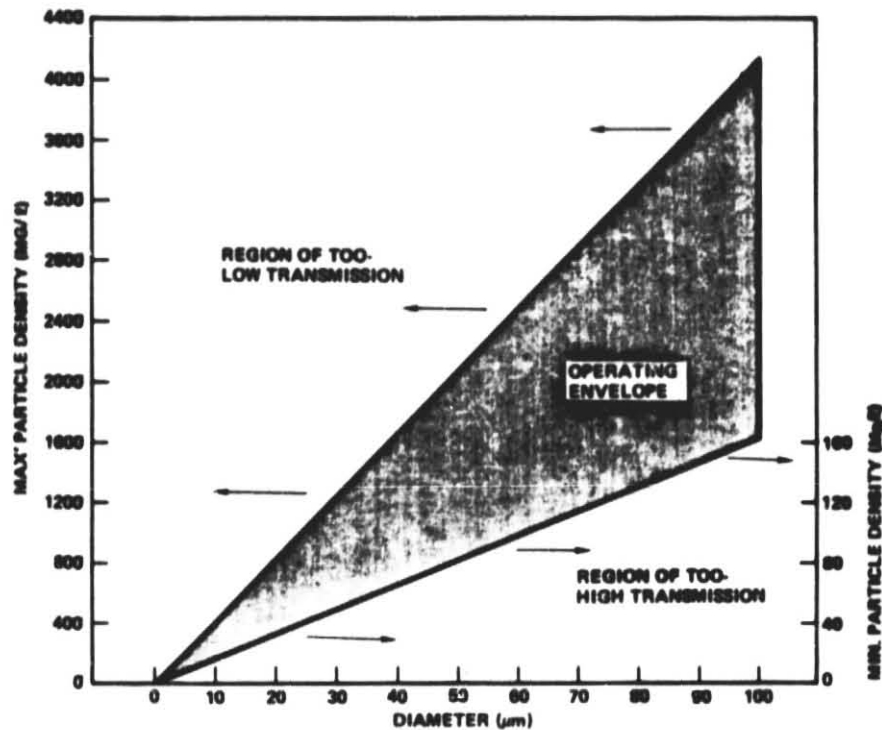


Figure 3.12 PARTICLE OPERATING ENVELOPE FOR SCATTERING

3.7.4 Accelerometers

The experiment requires a stable acceleration level of 10^{-4} or less. A science requirement exists to record the g levels to assist in data interpretation. A two axis accelerometer with a resolution better than $10^{-4}g$ will be mounted inside the experiment housing for these measurements. Determinations made with Prof. Berlad indicate that $10^{-4}g$ is the minimum g requirement.

ORIGINAL PAGE IS
OF POOR QUALITY

3.8 DATA ACQUISITION

Bandwidth of the data acquisition system must be sufficient for the various measurements it is used to record. The most rapid phenomena under observation is the flame front passage through the observation angle of a detector. For a 30 degree admittance half angle, a tube segment 3.2 cm (1.3 in) in length is observed by the sensor. A flame propagating at the highest anticipated velocity, 1 m/s, (3.3 ft/sec) will be observed for 32 msec. To resolve any structure (spatial resolution) of the flamefront signature five readings should be accomplished during flame passage. A minimum rate of 156 Hz is required by this condition. Mixing will be carried out over time spans on the order of 1 minute. To ensure accurate comparison of pre and post mixing homogeneity detector readings, very little drift should occur over this period. For this reason, system bandwidth should extend to nearly 0 Hz (D.C.). The data acquisition system will record four IR sensors and two axes of the accelerometer during test, for a total of six channels. To meet the bandwidth requirement, a total data rate of 936 Hz is required while in this mode. Photographic observation is planned for a 2.9 sec duration to cover 40 cm (15.7 in) of the tube. Data acquisition is required to respond to sensors along the entire tube and should be capable of 5.8 sec operation per tube. A total of 92.8 sec. One minute of mixing and 20 sec of relaxation time are planned for each tube during which homogeneity detector readings should be performed. An additional 1280 sec of recording time, possibly at lower data rates, are required by this function. The demands for data acquisition, in summary, are a bandwidth of D.C. to 936 Hz over a duration of 1373 seconds. For signal recording in digital form to 10 bit precision, a bit rate of 9360 Hz is required with total storage of 12.9×10^6 bits.

3.9 THERMAL CONTROL

A chassis fan in the enclosure is necessary to exhaust heat generated both during combustion and heat dissipation by instrumentation.

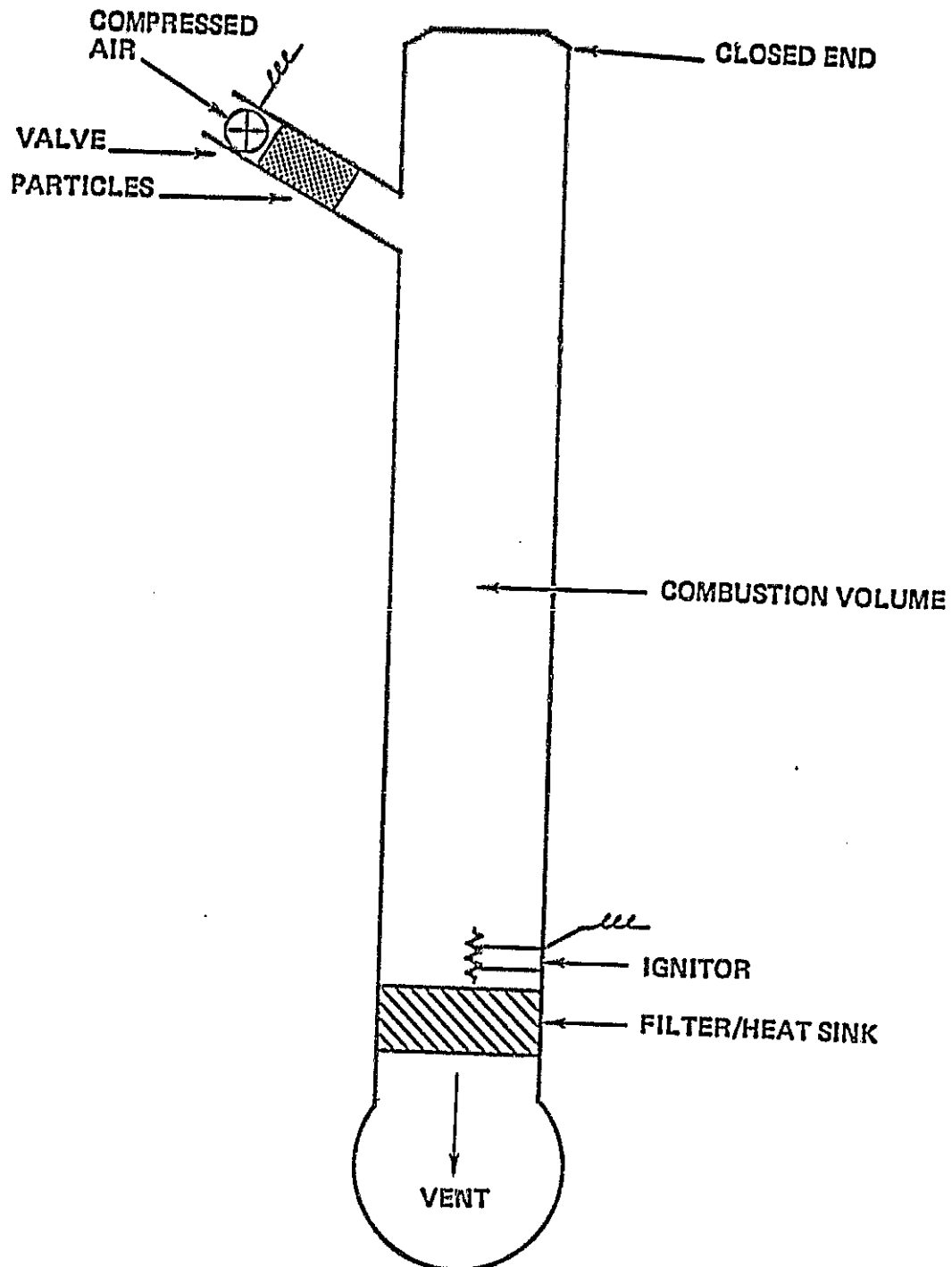
3.10 COMBUSTION OF POROUS SOLIDS EXPERIMENT CONCEPT

The results of the analyses in Section 3 are combined to give a concept upon which we based our preliminary design. The experiment is constrained to be placed in the mid-deck locker area and to occupy a four locker volume. The four locker volume can be 2 x 2 (Figure 2.7a) or 4 x 1 (Figure 2.7b). This represents long dimensions of 88 cm (34.7 in.) and 101 cm (39.8 in.) respectively. The maximum depth is 51.8 cm (20.4 in.) including the adaptor plate.

The concept evolved during the study. The concept for the tube is shown in Figure 3.13. The essential functions of the tube are internal to the tube, as far as this is possible. The overall tube length is the maximum permitted by accommodation of all functions into the prescribed volume. The vent, ignitor and particle injector all form part of the combustion tube system. One end of the tube contains the vent system. The other is closed. It must, however, interface with the mixer. The mixer can be internal to the tube (i.e., a propeller) or external. In the final concept the mixer is shown external to the tube.

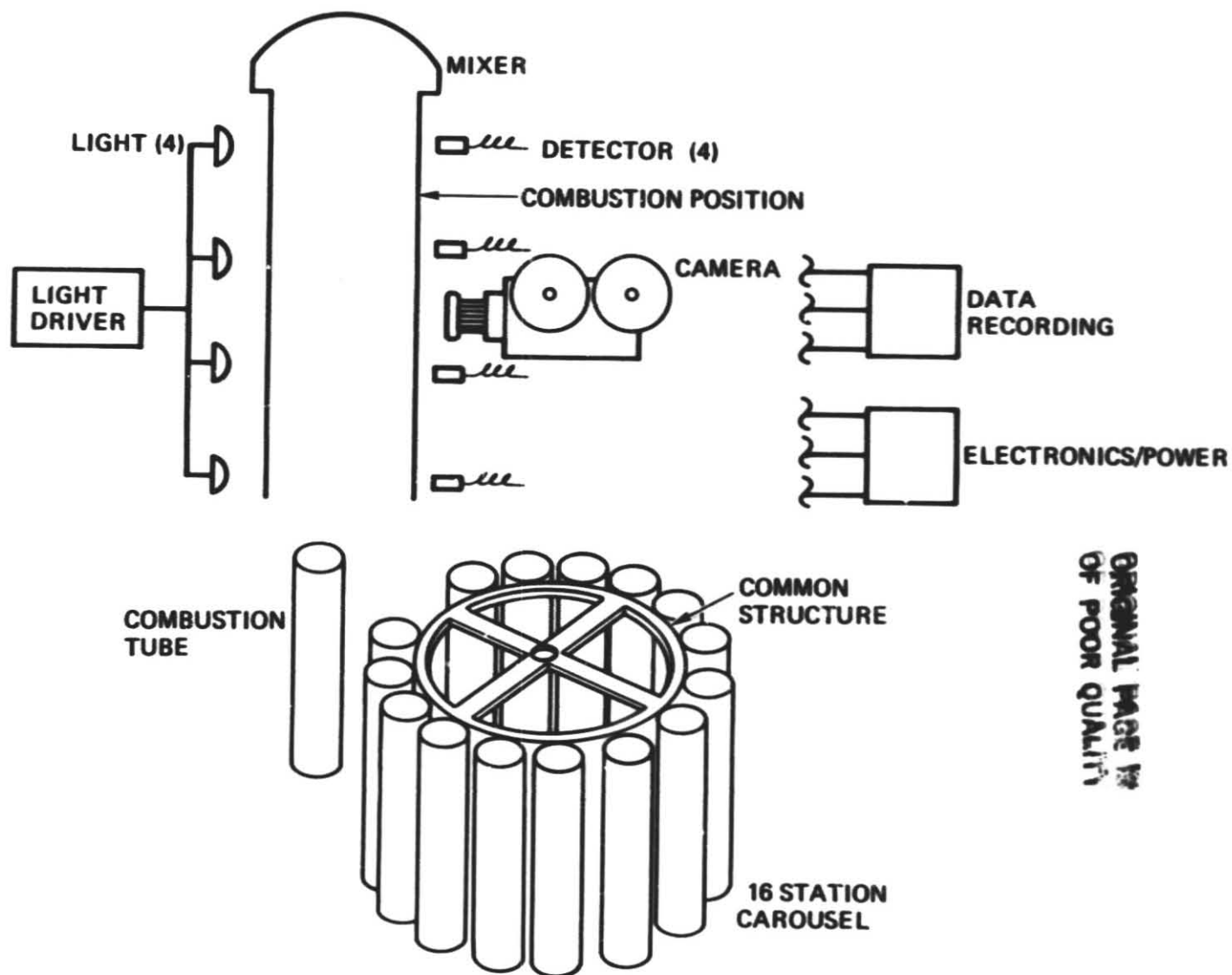
The entire experiment system is shown in Figure 3.14. There are 16 combustion tubes arranged in a carousel. Each tube rotates in turn to an experiment station. This station contains the mixer, or mixer interface and the transmission measurement system that will measure the mixing efficiency and determine the particle homogeneity. The detectors are also utilized to measure the rate of flame propagation. The detector outputs are fed into

ORIGINAL PAGE IS
OF POOR QUALITY



COMBUSTION TUBE SCHEMATIC

Figure 3.13 COMBUSTION TUBE CONCEPT



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 3.14 COPSE CAROUSEL CONCEPT

the data recording system. The high speed camera records the flame at two positions.

The concepts described here form the basis of our design given in Section 5.

4.0 LABORATORY EQUIPMENT DEVELOPMENT

Construction of laboratory equipment to carry out controlled tests of subsystems identified in the apparatus analysis phase serves several purposes.

- It provides an aid to the designer in visualization of the experimental devices and in selection of appropriate mechanical components.
- It allows testing component performance and aids decisions among competing designs.
- Experience is gained on the amount of operator intervention required and the difficulty of operator tasks.
- Improved concepts for components are often generated once the initial design is put into operation.

TRW designed and constructed laboratory equipment to test especially COPSE concepts of venting and particle mixing. The laboratory equipment was tested to the extent necessary to verify its satisfactory operation. The apparatus was then delivered to NASA Lewis Research Center for evaluation of several elements of the COPSE concept.

Descriptions of the elements constructed for the laboratory equipment and their integration for testing of design concepts follows. Appendix 9 contains the laboratory equipment operating notes supplied to NASA/LeRC with the apparatus. The appendix also includes a complete parts list.

4.1 SIMULATION OBJECTIVES

Laboratory equipment cannot properly simulate all the mechanisms relevant to operation of the Shuttle-installed apparatus at low gravity. For example, a cloud of particles at 1 g will not remain suspended in the tube without continuous mixing. The combustion phenomena are simulated with tests using premixed propane/air. The laboratory equipment is not meant to utilize prototype or protoflight hardware considered for the completed flight system. Rather, it is oriented toward examination of some of the fundamental physical processes supporting proper development of such hardware. The need for tests was indicated in several areas:

- Combustion Tube
- Exhaust Vent
- Particle Injector
- Particle Mixer
- Instrumentation

The combustion tube is central to the lab equipment and serves to verify the accessibility of data and to observe combustion behavior. It is also the structure to which the other devices must attach and be adapted.

A particle injection apparatus was tested to prove a concept for maintaining the particles in an inert (nitrogen) atmosphere prior to beginning an experiment. Further, the injector was to initiate the mixing process by providing a rough dispersion of particles in the combustion volume.

A spark ignitor was provided for initiation of combustion

tests of the vent and instrumentation devices. The ignitor's performance can also serve as a guide to ignition device design for the flight experiments. The vent systems are designed to allow the combustion process to proceed at isobaric conditions while preventing product gases and particles being emitted. Two vent system prototypes were constructed for evaluation under the NASA/LeRC test program.

Two instrumentation concepts were built for testing with the laboratory apparatus. Spatial homogeneity of particle mixing is measured by comparing the fraction of power of a beam of light passing through the combustion volume after being scattered by the particles in the beam's path at a few locations along the tube. The capability of the light scattering device to accurately measure mixing is to be tested. The photodiodes used as sensors in the light transmission measurement also detect the radiating flame front as it propagates past them. The signals generated by a series of photodiodes located along the combustion tube with flame passage permit accurate determination of the rate of flame propagation.

Table 4.1 summarizes the experimental devices and hardware development goals to be assessed through laboratory equipment construction and operation.

4.2 LABORATORY EQUIPMENT COMPONENTS

The assembly, appearance and operation of the laboratory equipment are described in this section. Specific design considerations and calculations are presented in Section 3. This portion of the report summarizes the components as they were constructed and delivered to NASA. Minimal operation of the equipment was necessary only to assure proper operation before delivery. The laboratory experience gained during this experimentation is also discussed.

Table 4.1 REQUIREMENTS AND CAPABILITIES OF THE LABORATORY EQUIPMENT

EXPERIMENT CONCEPT	DESIGN DEVELOPED IN APPARATUS ANALYSIS	LABORATORY EQUIPMENT CAPABILITY
<ul style="list-style-type: none"> • USE OF CYLINDRICAL TUBE TO CONTAIN POROUS AND COMBUSTION TEST VOLUME 	<ul style="list-style-type: none"> • PYREX TUBE WITH REMOVABLE END FITTINGS 	<ul style="list-style-type: none"> • ASSURE TUBE COMPATIBILITY WITH INJECTION AND VENTING DEVICES • TEST INSTRUMENTATION • TEST INJECTOR, MIXER, IGNITOR AND VENT SYSTEMS
<ul style="list-style-type: none"> • INTRODUCTION OF PARTICLES TO THE COMBUSTION TUBE IMMEDIATELY BEFORE INITIATION OF THE EXPERIMENT 	<ul style="list-style-type: none"> • COMPRESSED AIR INJECTION USING DOUBLE DIAPHRAGM PARTICLE COMPARTMENT 	<ul style="list-style-type: none"> • DETERMINE AIR PRESSURE AND FLOW RATE REQUIREMENTS • OBSERVE QUALITY OF INITIALLY ACHIEVED DISPERSION
<ul style="list-style-type: none"> • LARGE AND SMALL SCALE MIXING OF PARTICLES TO ACHIEVE FUEL DISTRIBUTION 	<ul style="list-style-type: none"> • ACOUSTIC MIXER • INTERNAL AERODYNAMIC MIXER • EXTERNAL AERODYNAMIC MIXER 	<ul style="list-style-type: none"> • MEASURE MIXER POWER REQUIREMENTS • DETERMINE OPTIMAL ACOUSTIC MIXER SIGNAL CONDITIONING • VERIFY AND COMPARE MIXER PERFORMANCE • ADDRESS PARTICLE/PARTICLE AND PARTICLE/WALL ADHESION PROBLEM
<ul style="list-style-type: none"> • INITIATION OF A PLANAR COMBUSTION WAVE BY IGNITION OF A FLAME KERNEL 	<ul style="list-style-type: none"> • SPARK DISCHARGE IGNITOR • TUBE CHARGING WITH A PROPANE/AIR MIXTURE 	<ul style="list-style-type: none"> • VERIFY IGNITOR PERFORMANCE • OBSERVE COMBUSTION WAVE STRUCTURE AND VELOCITY
<ul style="list-style-type: none"> • VENTING OF THE COMBUSTION TUBE TO MAINTAIN ISOBARIC REACTION ENVIRONMENT 	<ul style="list-style-type: none"> • OPEN FILTRATION VENT SYSTEM • EXPANDABLE CLOSED MEMBRANE VENT SYSTEM 	<ul style="list-style-type: none"> • ASSURE VENT/TUBE COM. • PERFORMANCE MEASUREMENT (PRESSURE RISE, EXHAUST ANALYSIS) • SYSTEM COMPARISON
<ul style="list-style-type: none"> • INSTRUMENTATION TO VERIFY FUEL SPATIAL UNIFORMITY AND TO MEASURE FLAME PROPAGATION RATE 	<ul style="list-style-type: none"> • LIGHT SCATTERING HOMOGENEITY DETECTOR • PHOTODIODE FLAME SENSOR 	<ul style="list-style-type: none"> • EVALUATE INSTRUMENTATION PERFORMANCE AND SUPPORT REQUIREMENTS • DETERMINE LEVEL OF OPERATOR INTERVENTION OR AUTOMATIC SYSTEM FOR MIXER CONTROL

4.2.1 Combustion Tube

The laboratory equipment experiments center around a single tube constructed to the dimensions defined in Section 2. The tube, made of borosilicate glass, is shown schematically in Figure 4.1. It is provided with end fittings to attach devices for testing mixing and tube venting, and side ports are provided for particle injection and ignition system access. Glass was chosen to provide visual access and ease of construction. The tube is rigidly mounted to a base plate so that external devices may be easily fitted to the tube. Two tubes were supplied. a polycarbonate safety shield was fitted to protect the operator in the event of accidental shattering of the tube during test. The actual flame tube is shown in Figure 4.2.

4.2.2 Particle Injector

A mechanism for injecting particles using air pressure was developed during apparatus analysis (Section 3). The particle injector allows determination of the quantity and pressure of air needed to inject the particles and to observe the distribution of particles in the combustion tube using this device. Reliability of operation and complete injection of the particle charge can also be investigated. The injector design is shown schematically in Figure 4.3. A pressure regulator and trigger valve are used to provide a partial charge of air at the desired pressure. Particles are carried downstream by the airflow into the combustion tube. During initial operation particles tended to collect at joints where the tube diameter narrowed, In the final device, 1/4" tubing was used along the entire length. The particles are held between 1/2 mil teflon diaphragms held in the fittings at either end of the metal tube. These diaphragms burst when pressurization occurs. In initial testing a brief pulse of

ORIGINAL PAGE IS
OF POOR QUALITY

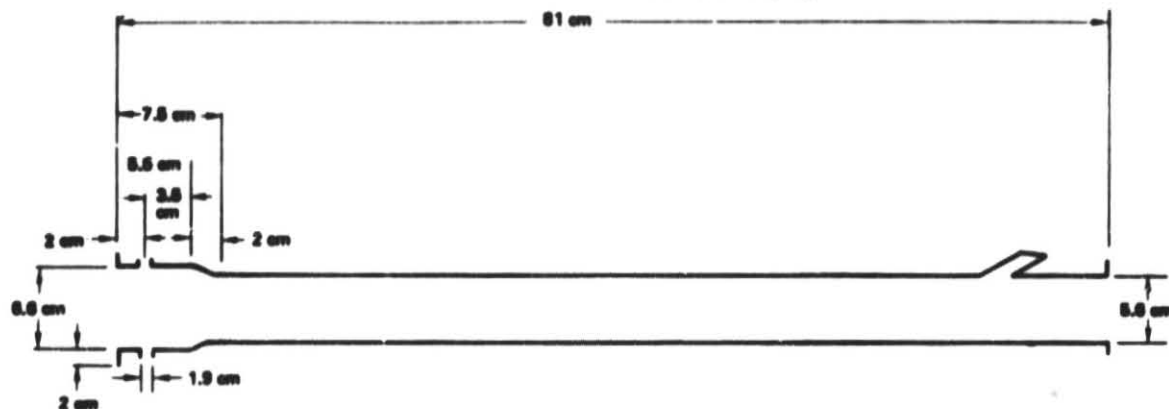


Figure 4.1 LABORATORY COMBUSTION TUBE DIMENSIONS

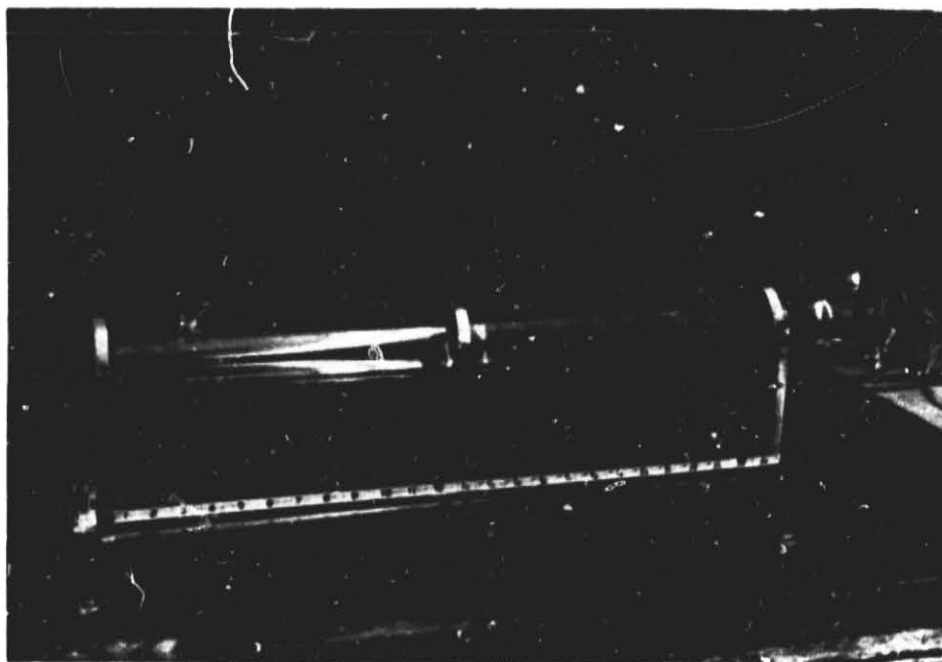


Figure 4.2 THE FLAME TUBE MOUNTED ON THE APPARATUS BASEPLATE

ORIGINAL PAGE 13
OF POOR QUALITY

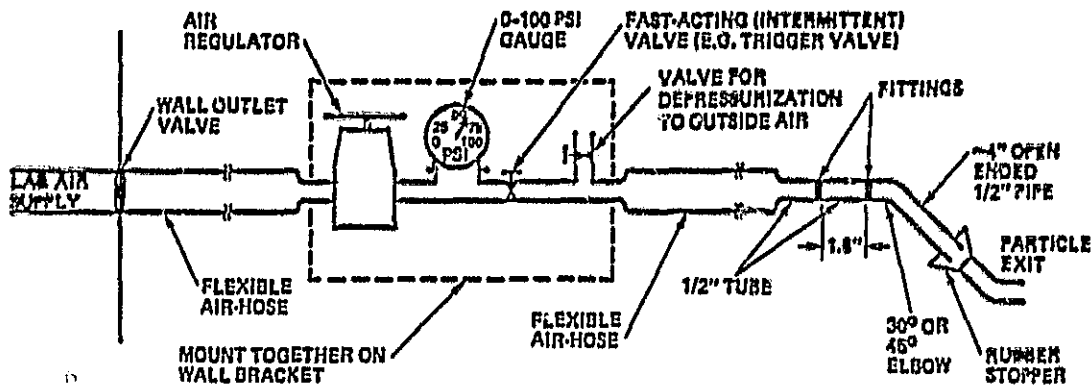


Figure 4.3 LABORATORY PARTICLE INJECTOR

air (< 1 sec) at 345 kPa (50 lb/in²) ruptured the diaphragms and dispersed the particles throughout the combustion tube. The Teflon ruptured by tearing and no material appeared to have separated from the diaphragm. No performance differences were experienced using a range of particulate materials including glass microspheres, corn starch and Al₂O₃ crystals.

4.2.3 Particle Mixer

Two mixing systems in three configurations were supplied to NASA. These were the acoustic mixer and the aerodynamic mixer, the latter with internal and external propellers. The mixing system includes a detector for determining spatial homogeneity. Each of these systems requires external electrical support. Figure 4.4 shows schematically the experimental configuration for the acoustic and aerodynamic mixers.

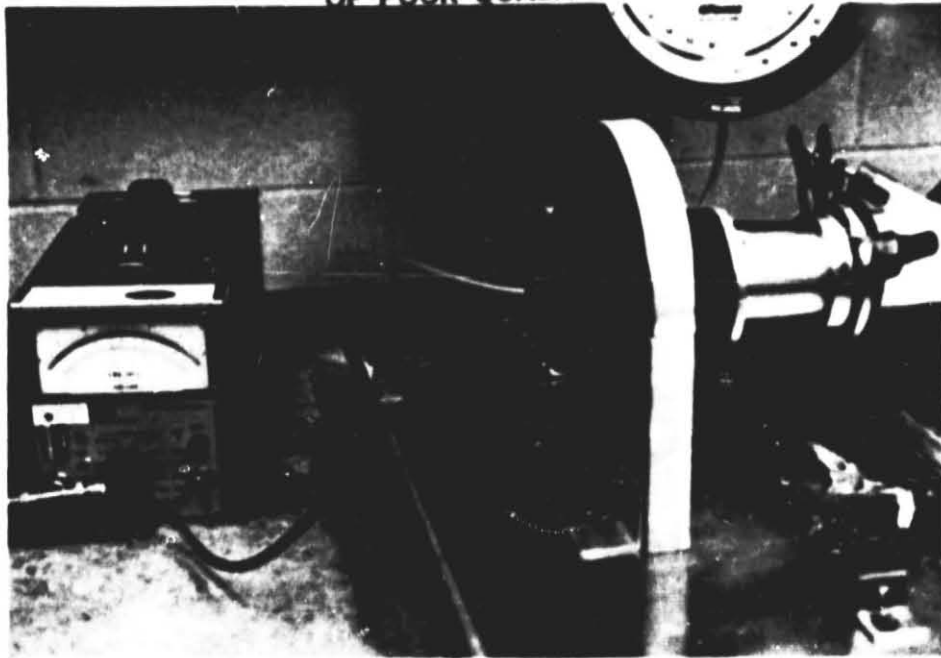


Figure 4.5 ACOUSTIC DRIVER MOUNTED TO THE COMBUSTION TUBE

3, smaller particles were sought for the experiment. These small particles appeared more likely to agglomerate so the scaling law could not be rigorously applied. Significant adhesion of the particles to the side walls was also observed. This adhesion as well as the particle to particle grouping remained after active mixing was stopped and appeared electrostatic in nature. The noise level during maximum power mixing was not quantified but was considered a distractive nuisance. The high elasticity of the glass tube makes it a good sound conductor. The greater hysteresis of the polycarbonate tube material should lower the ambient noise. This supposition was confirmed in telephone conversation with Mr. Thatcher Murray of JBL. Other improvements discussed with Mr. Murray included provision of an acoustic horn for improved impedance matching and custom ALNICO magnet construction for elimination of magnetic fields external to the driver housing.

Two aerodynamic mixers were provided for evaluation. The

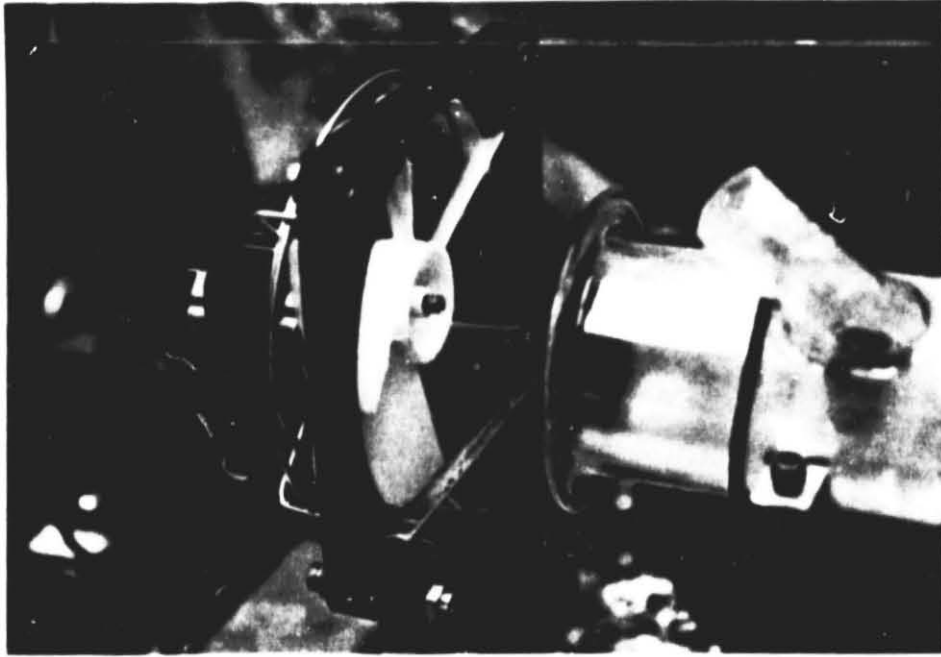
initial design called for an internal propeller with a shaft drive. This was coupled to a variable speed motor operating in the range 100-10,000 rpm. Very weak mixing was achieved using this device with the opposite end of the tube sealed to simulate the flame arrestor and vent system. A group of propellers of varying diameter and pitch were tested but none were capable of significant mixing. It is noted that the propellers were off-the-shelf items, designed as scale model boat propellers. Better performance can be achieved using propellers specifically designed to produce an air jet at high rotational speed.

A second aerodynamic mixing concept using an external fan was also tested. This fan uses a larger diameter (4 1/2 inch) blade expressly designed for moving air. Such a fan must be enclosed in a shroud to keep particles from exiting the test volume. Figure 4.6 shows the external fan in place near the tube end before the shroud was placed around it. Good mixing performance was achieved with this device. Its most serious drawback is provision for a shroud which introduces additional volume to the combustion zone.

The homogeneity detector system is shown in Figure 4.4 . The light sources are lens-end 2.25 W bulbs. Detectors are infrared photodiodes. The system is controlled through the junction box described in Section 3. Adjustment of trimming potentiometers in the junction was used to balance readings from the 3 detectors before initiation of a test. The detector signals were then observed to vary as the light impinging on them was scattered. Significant adhesion of particles to the tube walls prohibited testing of the system during mixing.

4.2.4 Ignition

The spark apparatus described in Section 3 was used to ignite a gas mixture for test of the vent and instrumentation



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 4.6 EXTERNAL FAN IN PLACE AT TUBE END BEFORE
ENCLOSURE BY SHROUD

system. The device created a blue spark of 1-3 cm length and dependably ignited the mixture on the first try. No attempt was made to ignite particle/air mixtures because of the difficulty in suspending particles under 1-g conditions and because of the large number of particles which adhered to the walls.

4.2.5 Combustion Gas Venting

The system used to test venting and flame detection are shown schematically in Figure 4.7. Two combustion gas vent systems were delivered to NASA for testing. They are the closed system with capture in an expandable membrane and an open scrubber system. Figure 4.8 shows the filtration system in place with the apparatus ready for operation. The system size was chosen for ease of assembly and for use in development tests. The system operated without problems but its scrubbing efficiency was not determined. Candidates for the expandable membranes were

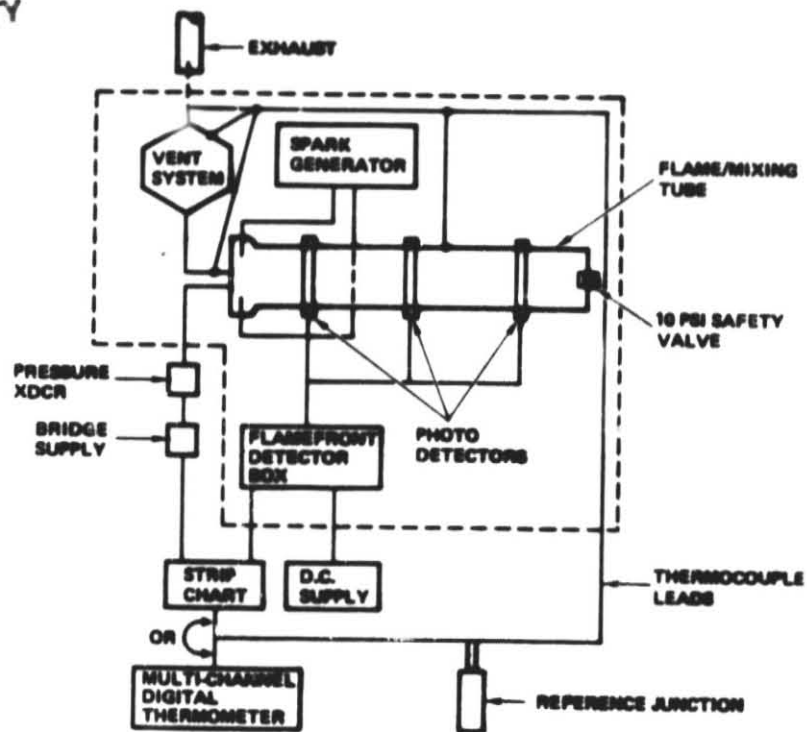


Figure 4.7 LABORATORY VENTING SCHEMATIC

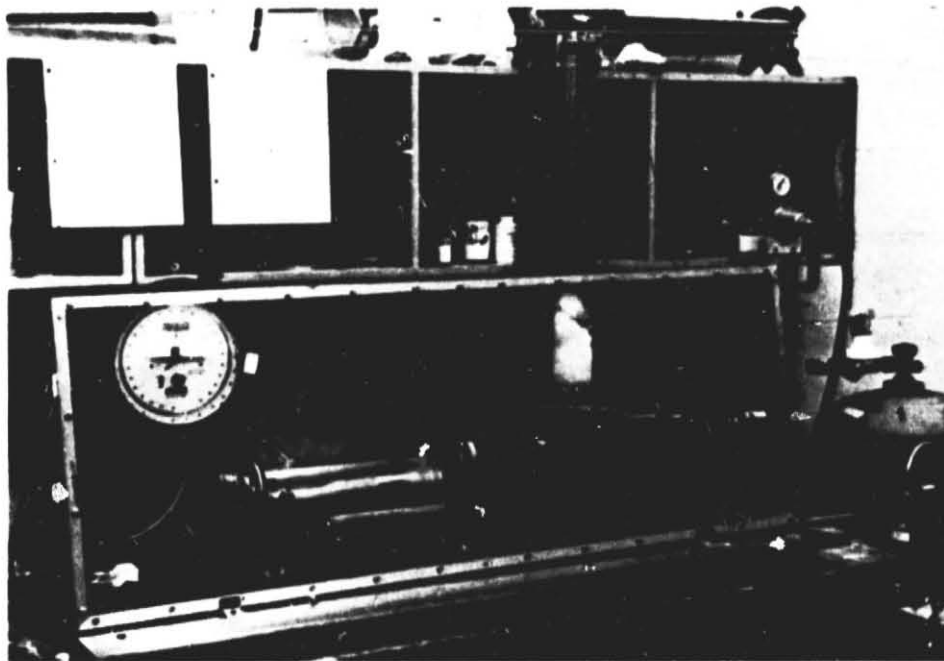


Figure 4.8 COMPLETE SYSTEM READY FOR VENT TESTING. THE COMBUSTION TUBE IS FITTED WITH SPARK ELECTRODES (RIGHT). THE SCRUBBER IS BEHIND IT.

delivered to NASA/LeRC without prior testing at TRW. The membranes were sized as single common reservoir devices, not as individual units for each tube.

4.2.6 Flame Shape, Speed and Detection

The premixed propane-air flame observed in laboratory testing will differ significantly from the combustion of suspended particles. Observations using this flame may still serve as a guide in component development. Upon ignition of the mixture a blue flame front develops normal to the tube longitudinal axis and propagates horizontally along the tube. A part of the flame did propagate through the region between the ignitor electrodes and the vent port.

When using premixed gas charges, care should be taken to avoid filling the vent system with combustible gas. Otherwise the backward propagating flame may travel through the entire vent system. The flame propagating through the main tube volume reaches the far end in about 1 second. This time is affected by the vent used. In one test, venting was provided ahead of the flame front instead of behind it. This resulted in a flame with an unsteady, rapid propagation. With the design vent configuration, no change in flame speed was observed by eye. The flame sheet deforms to a paraboloid as it propagates with the central portion moving more rapidly than the edge. The flame developed an overall depth of several centimeters through this mechanism. The flame front also became slightly unsymmetrical, probably due to buoyancy effects.

Flame detection was provided by the same sensors used in the mixing detectors. Each of them showed a trace on an oscilloscope as the flame passed its position. A repeatable signature of distinctive shape was derived for each sensor. Features within these signatures can be matched for measurement of the flame

propagation speed from a recording of sensor output.

During tests of the laboratory equipment, the flame tube and vent system were fitted with a pressure transducer and thermocouples. A Statham pressure transducer was mounted to the plate attached to the ignition end of the combustion tube. By monitoring tube pressure we verified that the vent was not restricting exit flow to an extent causing a pressure rise in the tube.

Thermocouples were placed on the tube outer wall and at the entrance and exit of the vent stack. These were used to confirm that no excessive temperatures were present at sensitive points in the apparatus. Data from these four sensors were recorded and a typical run is plotted in Figure 4.9. The recorder trace shows a spike across all channels corresponding to operation of the spark ignitor. There is a rapid pressure rise peaking at 2.3 psi during this first 100 ms of combustion. This corresponds with a temperature pulse to 540 C at the thermocouple immediately downstream of the combustion tube vent port. These two traces indicate that a flame propagated into the tube connecting the combustion tube and the vent system. As pointed out earlier this is probably a result of the use of a gas premixture in place of actual particle combustion. To prevent this occurrence, the connecting tube was filled with borosilicate glass wool. A porous metal plate will be incorporated at the exit in the preliminary design. In the preliminary design a porous plate will act as a filter and prevent flammable particles from reaching the vent system. After these initial transients, temperatures remained low, with the outer wall of the tube exhibiting a barely discernable temperature rise. The final gas temperature at the tube exit did not exceed 100 C. The pressure during the remainder of the experiment remained steady at about 0.1 lb/in² (gauge). This pressure change is small. However, the combustion tube and fittings were not leak tested. Therefore it is impossible to know precisely what fraction of overpressure may

have been relieved through leakage. The observation of the momentary pressure spike and the small value of the steady state pressure indicates the apparatus should be adequate to yield usable pressure data in the range observed.

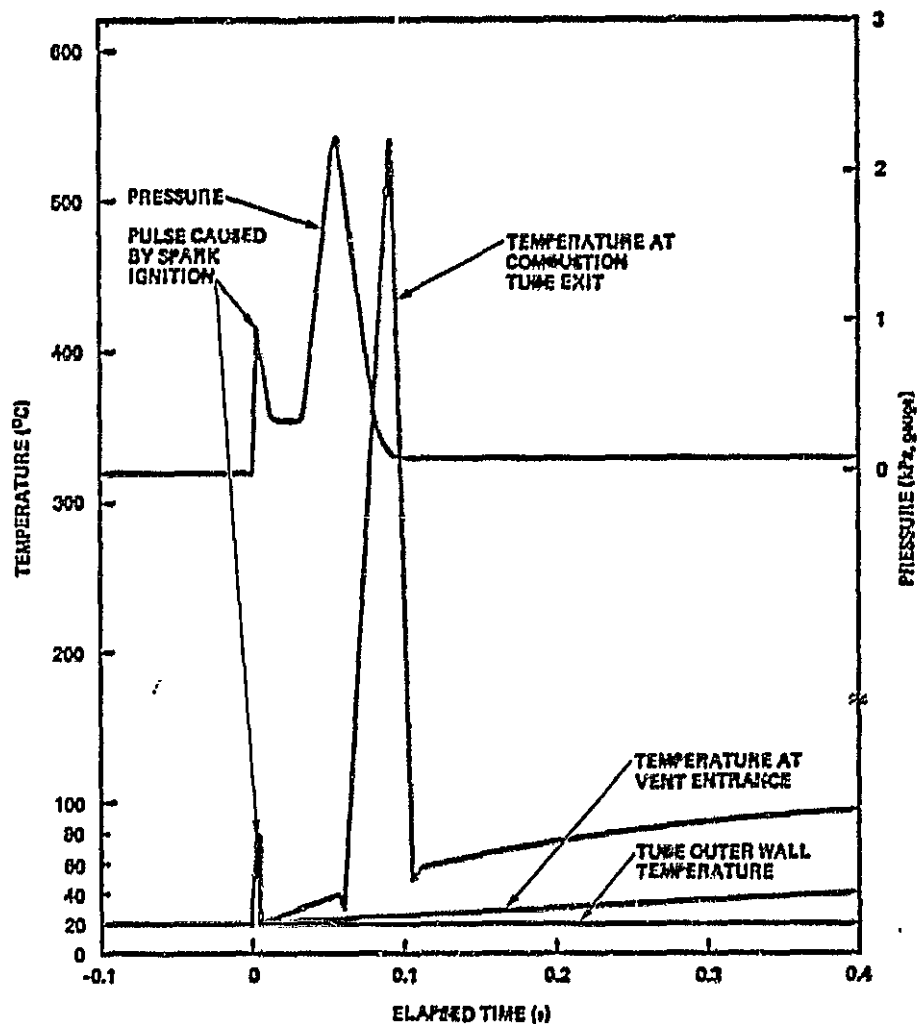


Figure 4.9 TYPICAL SENSOR DATA FROM LABORATORY TEST

ORIGINAL PAGE IS
OF POOR QUALITY

5.0 COPSE SUBSYSTEM DESIGN

The COPSE preliminary design is based upon the analyses made in Section 3.0 and follows directly from the integrated concept given in Section 3.9. The build-up of the laboratory equipment and subsequent testing at LeRC have been used as design inputs. The current design utilizes

- Four vertical locker volumes
- Two light-weight single adaptor plate interfaces
- Overhang into the top and bottom locker volume
- One mid-deck bus to supply power requirements.

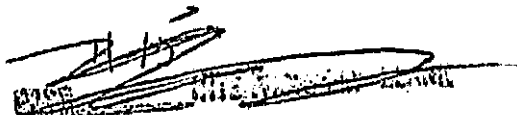
The subsystems designed are all accommodated within the volume available.

The overall design is based upon the "closed tube" approach. In this design all of the functions except instrumentation and control are independent for each tube.

The overall system layout is discussed in Section 7.0. The following subsections treat the design of each subsystem.

5.1 COMBUSTION TUBE

The combustion tube design is shown in Figure 5.1. Polycarbonate was chosen as the material to meet the requirements of optical access, resistance to rupture and shatter and low inflammability. The overall length of 81 cm (31.88 in) is accommodated in the experiment volume with allowances for the



vent system and support structure. The tube diameter is 5.6 cm (2.20 in) I.D. This size is the largest which may be accommodated in the available space. If the flight tubes are custom fabricated, a 5.0 cm (1.97 in) I.D., remains an option. The 5.6 cm diameter tube is accommodated in the design and is consistent with maintaining as large a cross section as possible. The ignition section of the tube is 6.6 cm in diameter. A tapered contraction from 6.6 cm to 5.6 cm is utilized from the ignition section to the main tube body to assure uninhibited flame front development. Abrupt changes in diameter are avoided so that particles do not accumulate in corners during injection and mixing. The ignition section is of 6 cm (2.36 in) length, the transition section is 2 cm (0.79 in) long and the main constant diameter section is 73 cm (28.74 in) long. The 75 cm (29.53 in) length specified in the science requirements is provided. The design wall thickness is 2.5 mm (0.094 in). This is almost twice as thick as that required for structural and thermal stress. It was chosen because it is a standard casting wall thickness and to leave a margin in the design either for later weight saving or to enhance tube strength.

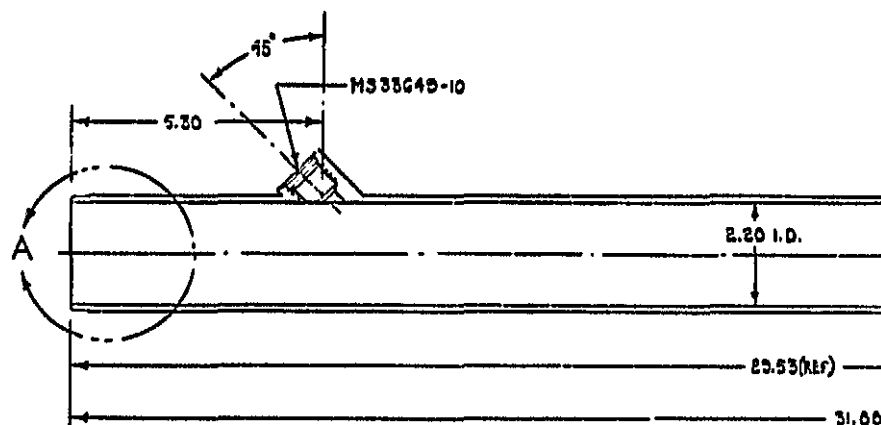
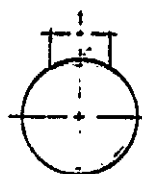
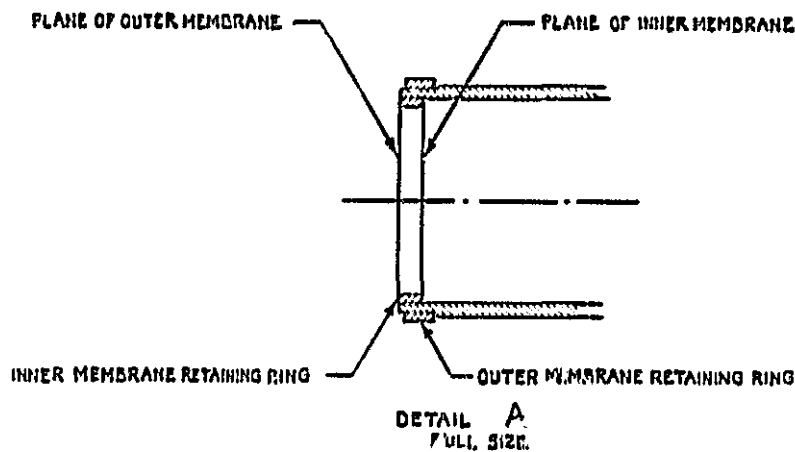
A double membrane is sealed at the tube's narrow end (detail A Figure 5.1). This membrane is of aluminum deposited on 1 mil mylar. It does not significantly interfere with acoustic energy coupling into the tube and retains the closed tube approach. Optimum energy transfer requires that the membrane not be pulled taut. The second, inner diaphragm provides a dead space which will not contain any particles. If the flamefront damages the first diaphragm the integrity of the closed system will not be violated.

Detail B (Figure 5.1) shows the placement of a sintered metal filter at the tube exit. The filter is of 0.32 cm (1/8 in) thick sintered nickel with a 10 μ m maximum pore size. It prevents particles from entering the vent system and acts as a heat sink to cool the combustion products. The metal plate is .

INCH SCALE

FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY



ORIGINAL PAGE IS
OF POOR QUALITY

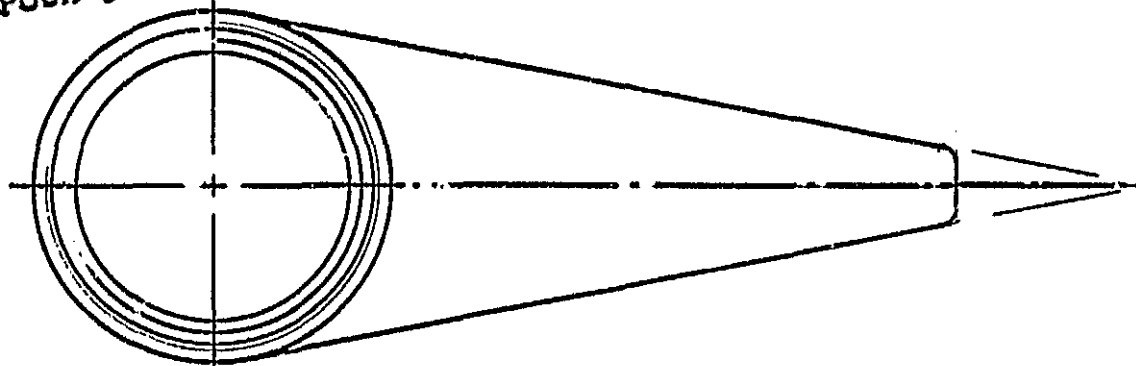
NOTES: UNLESS OTHERWISE SPECIFIED

1.

~~PRECEDING PAGE BLANK NOT FILMED~~

USED ON	CHIT	FILE
APPLICATION		

ORIGINAL PAGE IS
OF POOR QUALITY



COMBUSTION TUBE (REF)

SEAL

FILTER

FLEXIBLE ENVELOPE

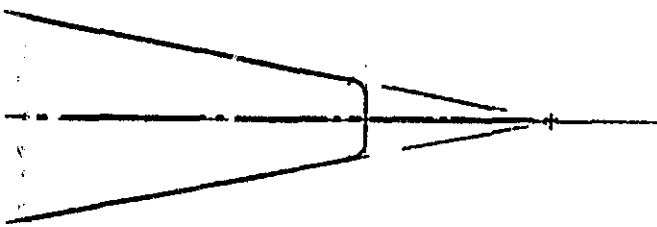
ENVELOPE CONTAINER

FOLDOUT FRAME

PRECEDING PAGE BLANK NOT FILMED

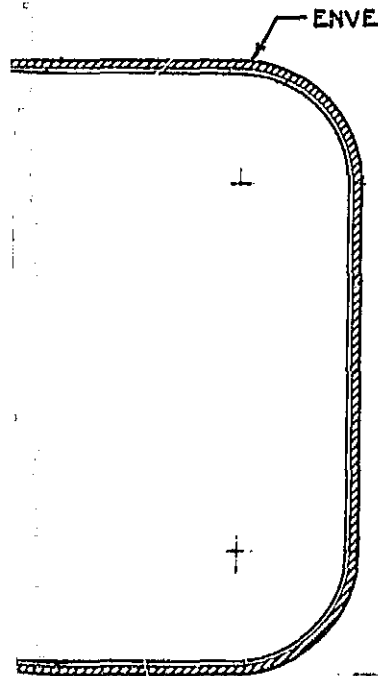
C-2

ORIGINAL PAGE 18
OF POOR QUALITY



ENVELOPE

ENVELOPE CONTAINER



FOLDOUT FRAME

FILMED

EXHAUST ACCUMULATION SYSTEM

SIZE	FSCM NO.	REV
C	11982	L 702506
SCALE FULL	SHEET 1 OF 1	

SYSTEMS 3408 REV. 9-78

Figure 5.2 COPSE VENT SYSTEM

sized to maintain low vent system pressure rise, providing the isobaric combustion conditions required.

The metal plate seats directly on top of the seal coupling the tube to the vent (Fig. 5.2). The vent attachment includes a vent (gas bag) seal that prevents particles or toxic gases from exiting the membrane. Two screws attach the gas bag shroud to the tube.

The particle injection system is attached through a fitting near the upper end of the tube. Also, a boss is provided that allows insertion of the ignition electrodes into the tube. Tube components are listed in Table 5.1.

Table 5.1 TABLE COMPONENTS

MAIN BODY	Length 73 cm (28.7 in.) I.D. 5.6 cm (2.2 in.)	Polycarbonate
CONTRACTION SECTION	Length 2.0 cm (0.79 in.) I.D. Smooth Taper from 5.6 cm (2.2 in.) to 6.6 cm (2.6 in.)	"
IGNITION SECTION	Length 6.0 cm (2.4 in.) I.D. 6.6 cm (2.6 in.)	"
WALL THICKNESS	2.4 mm (0.094 in.)	"
INJECTION PORT	I.D. 2.22 cm (0.875 in.) 45° Angle to Tube	"
MIXER - END ENCLOSURE	2 x 25 μ m (0.001 in.) Sheets Separated by 1 cm (0.39 in.)	Aluminum Vacuum Deposited on Mylar
VENT - END ENCLOSURE	1 cm thick 6.6 cm diameter disk	Sintered Nickel 10 μ m Pore Size

5.2 PARTICLE INJECTOR

The particle injector design is shown in Figure 5.3. The particles are contained in an inert, dry atmosphere inside a

PRECEDING PAGE BLANK NOT FILMED

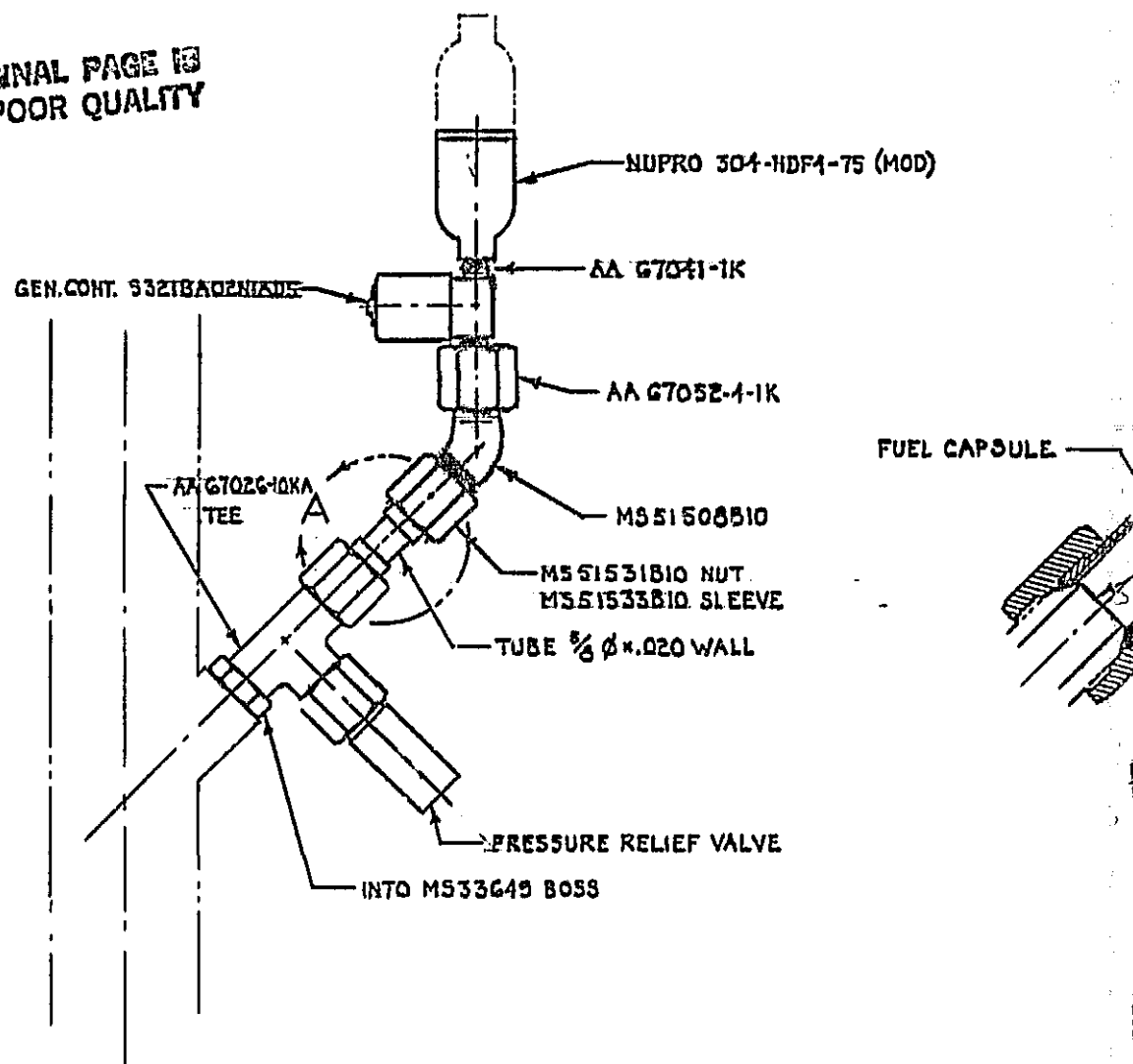
stainless steel tube between two 0.5 mil teflon membranes shown in Detail A. They are injected into the combustion tube upon opening of an 11 cm³ (0.67 in³) gas bottle charged to 1.01 MPa (147 lb/in²) with dry air. The compressed air release is actuated by a solenoid valve. A 34 KPa (5 lb/in²) pressure relief valve is collocated with the injector. The valve will function as a safety release to prevent significant back pressure buildup within the tube during the experiment. Because the valve opens at a much lower pressure than the injection pressure the valve is located between the particle cannister and the open tube. The vent system will accommodate the additional gas volume introduced by the particle injector. The maximum pressure rise induced by the sudden introduction of gas is 5 kPa (0.7 lb/in²). A sintered 10 m screen is provided at the exit to ensure no particles exit through the valve. Injection components are listed in Table 5.2.

Table 5.2 INJECTOR COMPONENTS

<u>COMPONENT</u>	<u>DIMENSION</u>	<u>MATERIAL</u>
Particle Cartridge	I.D. 1.46 cm (0.57in) length 6.0 cm (2.4in)	Stainless steel
Diaphragm	2x12.7µm thick	Teflon
Solenoid Valve	See figure	Stainless steel
Air Bottle	11cm ³ (0.67 in ³)	Stainless steel
Safety Valve	See Figure	Aluminum Body

(FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

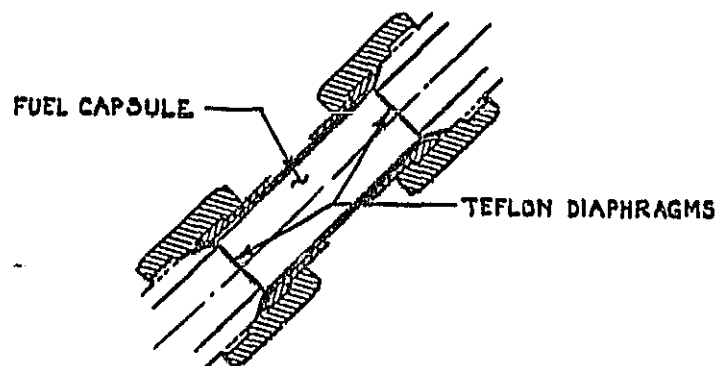


PRECEDING PAGE BLANK NOT FILMED

2 FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

NUPRO 304-HDF4-75 (MOD)
AA G7041-1K
AA G7052-4-1K
MS51508B10
MS51531B10 NUT
MS51533B10 SLEEVE
TUBE $\frac{5}{8}$ ϕ \times .020 WALL



DETAIL A
FULL SIZE

PRESSURE RELIEF VALVE
45 BOSS

NOT FILMED

FUEL INJECTION SYSTEM			
SIZE	FSCM NO.		REV.
C	11982	L 702505	
SCALE & NOTES		SHEET 1 of 1	

Figure 5.3 PARTICLE INJECTION SYSTEM

SYSTEM 242 REV. 9-75

5.3 PARTICLE MIXING

Acoustic mixing is selected to achieve homogeneous particle distribution. The acoustic mixing device requires an electrical signal supply (audio driver) and mechanical structure for its installation and support. Figure 5.4 shows the overall experiment. The acoustic mixer is mounted at the top of the enclosure, supported from the carousel center post. The driver can be lifted to allow tube rotation. The location chosen allows the operator to easily latch the driver into place and permits visual access to the tube under test. A corner location is required to allow centering of the driver over the tube while fitting the larger waist of the transducer inside the allocated space. The driver is a JBL model 2425 H chosen because of its power capability, efficiency and unique titanium diaphragm. The metal diaphragm eliminates any combustion hazard from contact with burning particles. It will be specially manufactured using an AlNiCo magnet to minimize EMI. A matching section will be provided to adapt the driver output to the tube diameter. This section will ensure efficient energy coupling. Provision is made to bring the driver into compressive mechanical contact with the tube sides through a soft diaphragm. This will also minimize the externally radiated sound.

The device will be driven by a 25 watt (rms) sinusoidal signal. The signal will alternate between tube resonance points at approximately 1050 Hz and 1275 Hz. Switching between the two resonances will be at 1 Hz. The operator will be provided with trim controls to tune each of the signals to resonance. Mixer components are shown in Table 5.3.

5.4 IGNITOR

Detail B of Fig. 5.1 shows the provision for a low voltage

ignitor using zirconium foil combustion. Each tube will be individually connected electrically. Ignition for the tube in the test position will be controlled by a demultiplexer in the control electronics with the selected tube shown on a front panel indexer. At ignition, 6 volts will be applied across the electrodes which are bridged inside the tube by a 71 mg bundle of striated zirconium foil. Joule heating raises the foil temperature to its ignition point and the burning foil will ignite the particle cloud.

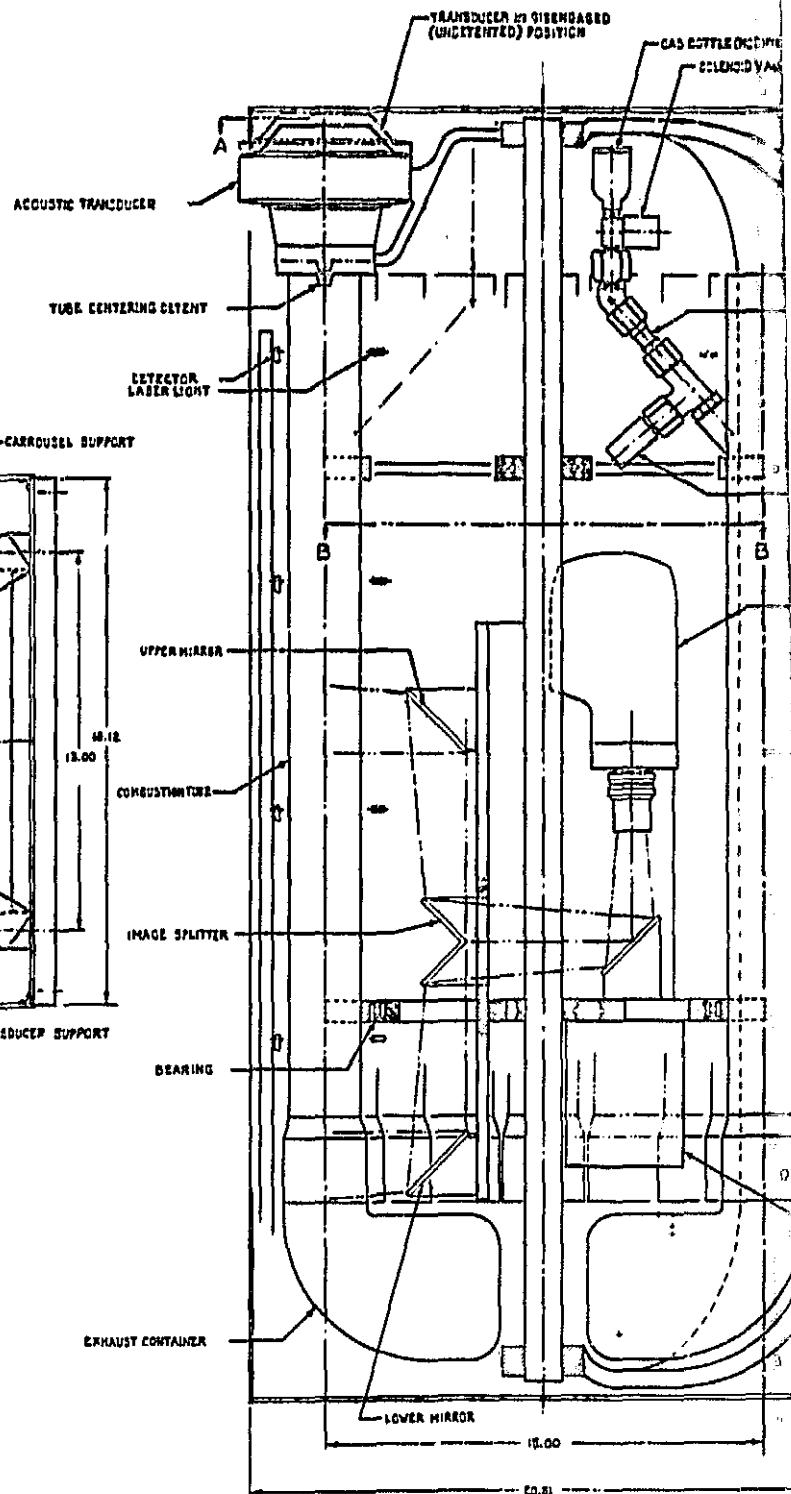
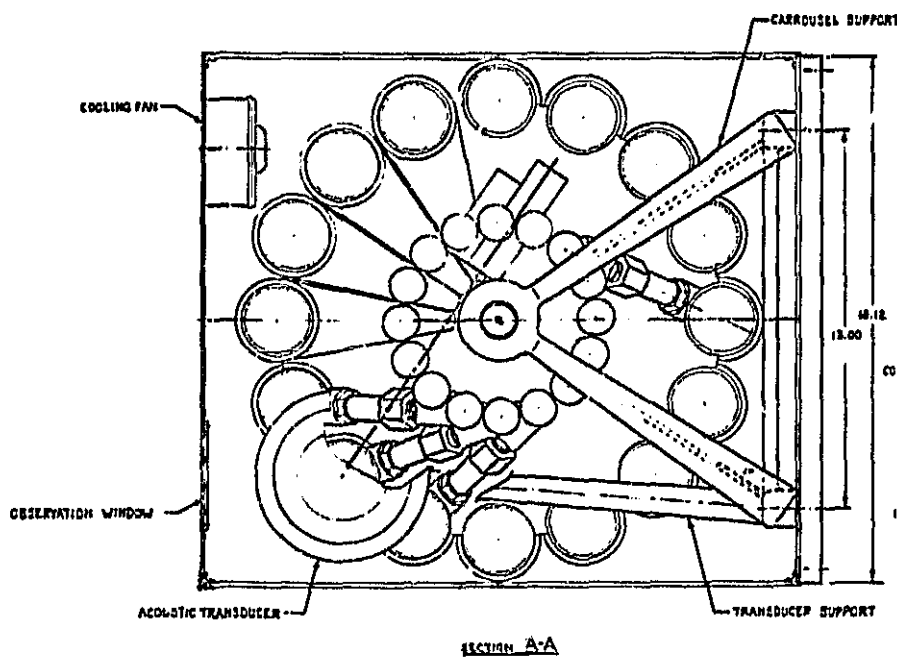
Table 5.3 MIXER COMPONENTS

JBL 2425H DRIVER (MODIFIED)	146 mm diameter 10 mm depth	Titanium Diaphragm AlNiCo Magnet
AUDIO SIGNAL GENERATOR AND AMPLIFIER	4.8 Kg	-
DRIVER SEAT	I.D. 5.5 cm (2.2 in.)	Buna-N Rubber

5.5 COMBUSTION GAS VENT

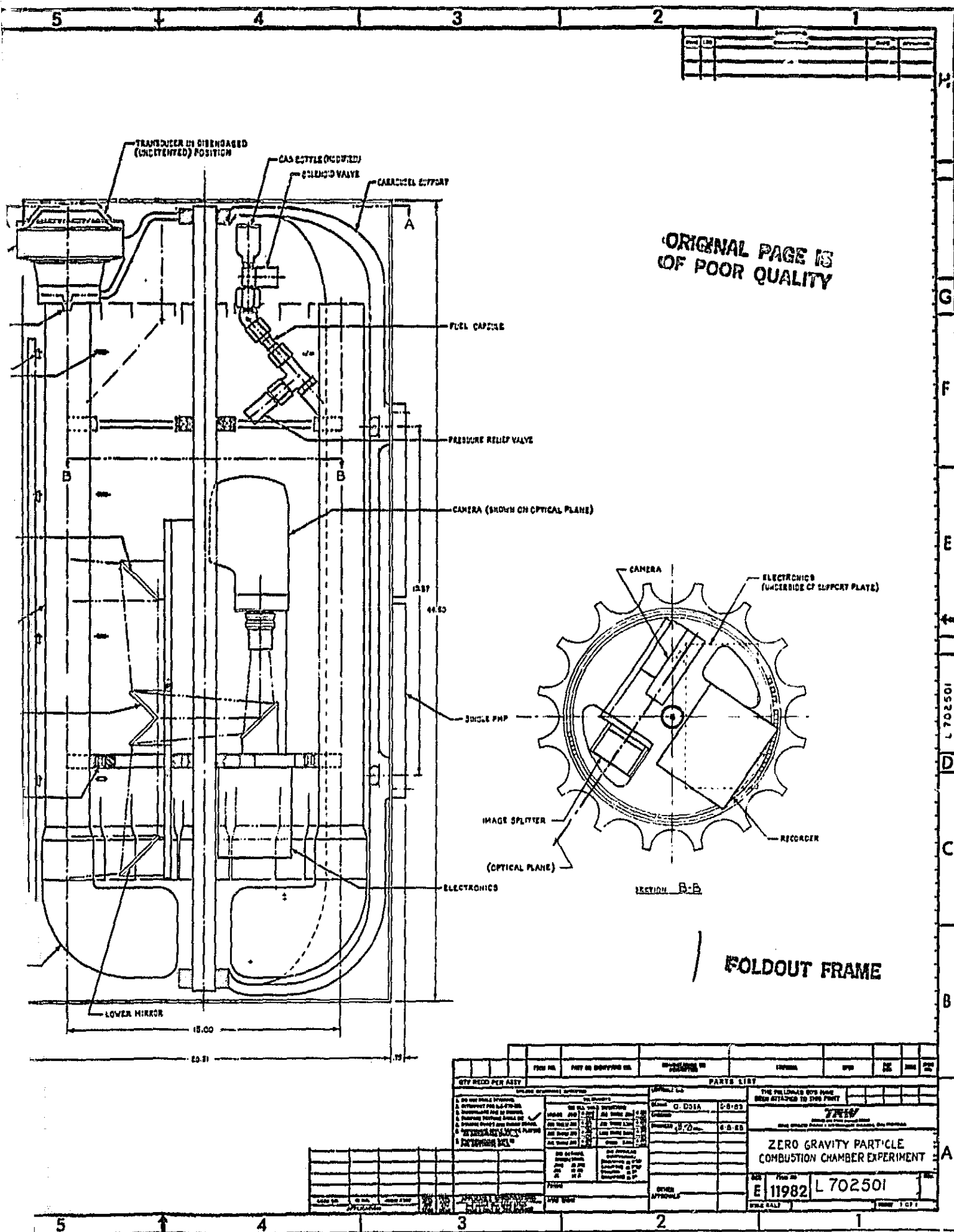
Venting of combustion product gas is accomplished by using a collapsed, enclosed membrane. The gas exits through a sintered nickel plate at the base of the ignition region (Figure 5.2). The membrane is a sealed, folded envelope of 2.5 μ m (1 mil) mylar with vacuum deposited aluminum. Fully expanded it has a volume of 900 cm³ (55 in³). The membrane is tailored to fit inside of the wedge-shaped enclosure shown at the bottom of the tube in Figure 5.5. The accumulation system is shown in detail in Figure 5.5. The enclosure is made of fiberglass. It provides a rigid housing to support the membrane to strengthen it. It also eliminates particle loss if the membrane ruptures. The enclosure will have a matrix of small holes (0.1 mm, 0.004 in diameter) in

ORIGINAL PAGE 13
OF POOR QUALITY



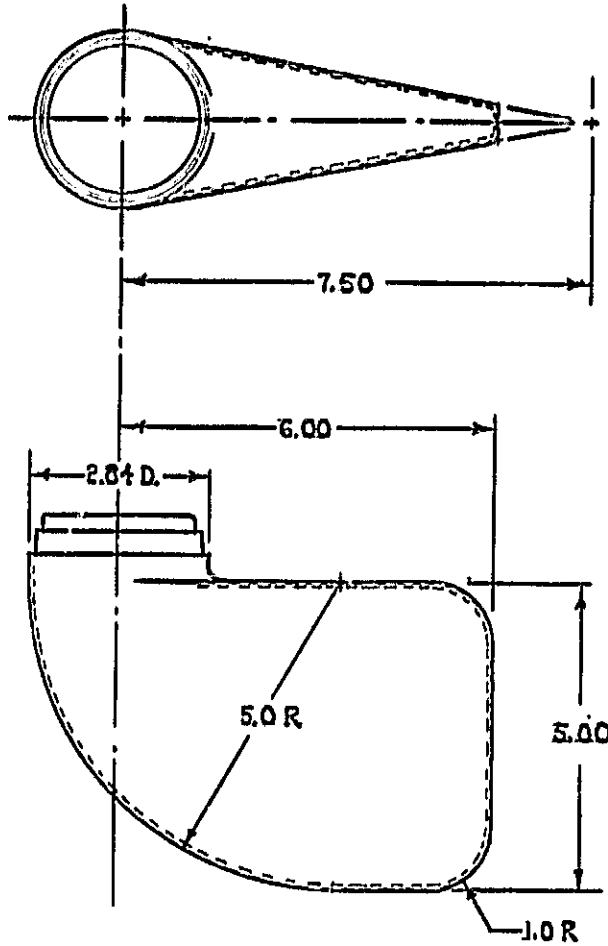
NOTES: UNLESS OTHERWISE SPECIFIED

2 FOLDOUT FRAME

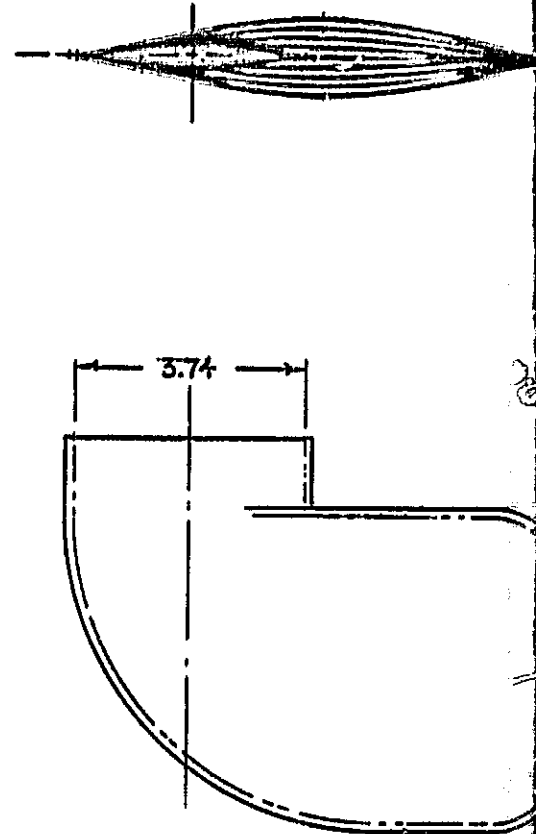


FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY



FIBERGLASS EXHAUST ENVELOPE CONTAINER



ALUMINIZED MYLAR FLEXIBLE ENVELOPE

NOTES: UNLESS OTHERWISE SPECIFIED

1.

PRECEDING PAGE BLANK NOT FILMED

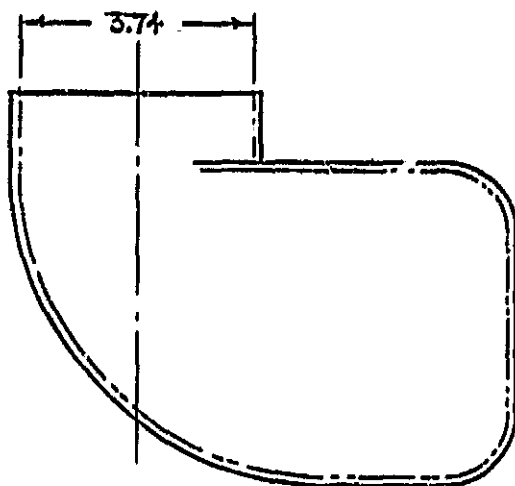
USED ON	CI NO.	NEXT ASSY	NEXT ASSY QTY REQ'D	FINAL ASSY QTY REQ'D
APPLICATION				

FSCM NO.		PART OR IDENTIFYING NO.	
QTY REQD PER ASSY			
UNLESS OTHERWISE SPECIFIED			
1. DO NOT SCALE DRAWING. 2. INTERPRET PER MIL-STD-100. 3. DIMENSIONS ARE IN INCHES. 4. SURFACE TEXTURE SHALL BE 5. REMOVE BURRS AND SHARP EDGES. 6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING. 7. PARENTHEICAL DATA IS FOR REFERENCE ONLY.		TOLERANCES ON ALL HOLE DIAMETERS UNDER .010 $\pm .002$.010 THRU .125 $\pm .004$.125 THRU .250 $\pm .006$.251 THRU .500 $\pm .008$.501 THRU 1.000 $\pm .010$ 1.001 THRU 2.000 $\pm .012$ 2.001 THRU 3.000 $\pm .015$ OVER 3.000 $\pm .020$	
		ON DECIMAL DIMENSIONS: .001 $\pm .001$.002 $\pm .002$.003 $\pm .003$.004 $\pm .004$.005 $\pm .005$.006 $\pm .006$.007 $\pm .007$.008 $\pm .008$.009 $\pm .009$.010 $\pm .010$	
		ON ANGULAR DIMENSIONS: MACHINED $\pm 30'$ LOCATING $\pm 15'$ FORMED $\pm 5'$ CHAMFERS $\pm 5'$	
		FINISH	
HEAT TREAT		APPLICABLE SPECIFICATIONS	
THE ABOVE TRW DSG SPEC FORM A PART OF THIS DRAWING			

REVISIONS			
LTN	DESCRIPTION	DATE	APPROVED

ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME



ALUMINIZED MYLAR FLEXIBLE ENVELOPE (PLEATED)

L 702509 1 4


	FSCM NO.	PART OR IDENTIFYING NO.	HOUSING/LABEL OR DESCRIPTION	MATERIAL	SPCO	REF DES	ITEM NO.					
PER ASSY	PARTS LIST											
UNLESS OTHERWISE SPECIFIED			CONTRACT NO.	THE FOLLOWING EQ'S HAVE BEEN ATTACHED TO THIS PRINT								
DRAWING: R MIL-STD-100, WE IN INCHES, TURE SHALL BE AND SHARP EDGES. PPLY BEFORE PLATING ON COATING. L DATA IS E ONLY.	TOLERANCES		DRAWN G. D03A	G-22-83	 ONE SPACE PARK • REDONDO BEACH, CALIFORNIA							
	ON ALL HOLE DIAMETERS		CHECKED									
	UNDER .010	+0.002 -0.005	.001 THRU .750	+0.002 -0.001								
	.010 THRU .125	+0.004 -0.001	.751 THRU 1.000	+0.010 -0.001								
	.126 THRU .250	+0.004 -0.001	1.001 THRU 2.000	+0.011 -0.001								
	.251 THRU .500	+0.004 -0.001	OVER 2.000	+0.011 -0.001								
	ON DECIMAL DIMENSIONS:		ON ANGULAR DIMENSIONS:		EXHAUST ACCUMULATOR							
	XXX ± .010		MACHINED ± 0°30'									
	XXX ± .005		LOCATING ± 0°20'									
	X ± .001		FORMED ± 0°									
	CHAMFERS ± 0°											
FINISH			OTHER APPROVALS		SIZE	FSCM NO.	REV					
SPECIFICATIONS					C	11982	L 702509					
HEAT TREAT					SCALE HALF		SHEET 1 OF 1					

Figure 5.5 COPSE VENT DETAIL

it so that air can escape as the membrane expands and fills. Multiple small pores permit unimpeded airflow while providing mechanical support of the membrane.

5.6 INSTRUMENTATION

The instrumentation identified for the COPSE experiment is

- 1) Camera
- 2) Flame Sensors
- 3) Mixing Sensors

5.6.1 Camera

The camera shall be a Photosonics model 16 mm - 1 VN equipped with a pulsed LED timing marker. It will be run at a maximum of 100 frames per second and will hold film cassette of 225 feet, x 2 mil film. Optics for the camera are designed to yield a field-of-view (FOV) split into two parts by a prism. The optical system is shown in Figure 5.6, It will record the ignition region and an intermediate portion of the tube. The FOV at each location is 4.7 centimeters long and 7 cm wide.

5.6.2 Flame Sensors

The flame propagation rate is determined from the time record of the flamefront signature on four phototransistors. These devices are evenly spaced along the test section (Figure 5.4). They will be Texas Instruments TIL-81 devices. Their signals will be digitized and recorded using a Lockheed Electronics 4200 recorder. Analogue to digital conversion will

PRECEDING PAGE BLANK NOT FILMED

be carried out at 250 Hz per channel to a precision of 12 bits.

5.6.3 Mixing Sensors

The phototransistors used for flame sensors will form a part of the particle homogeneity apparatus by measuring light transmission through the cloud of dispersed fuel particles. Each phototransistor will be directly across the tube from a 5 watt, colimated quartz-halogen light source. Before mixing, light outputs will be balanced to provide equal signals at four phototransistors. As the particles are dispersed, they attenuate this transmitted light, decreasing the output of each phototransistor. A front panel display will consist of a matrix of LED's, compsed of 4 columns each with 16 elements (Figure 5.7). Each column will represent the signal from one

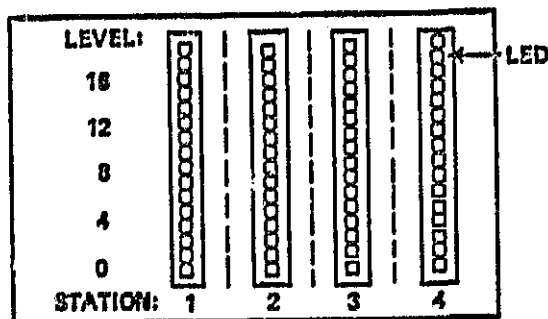
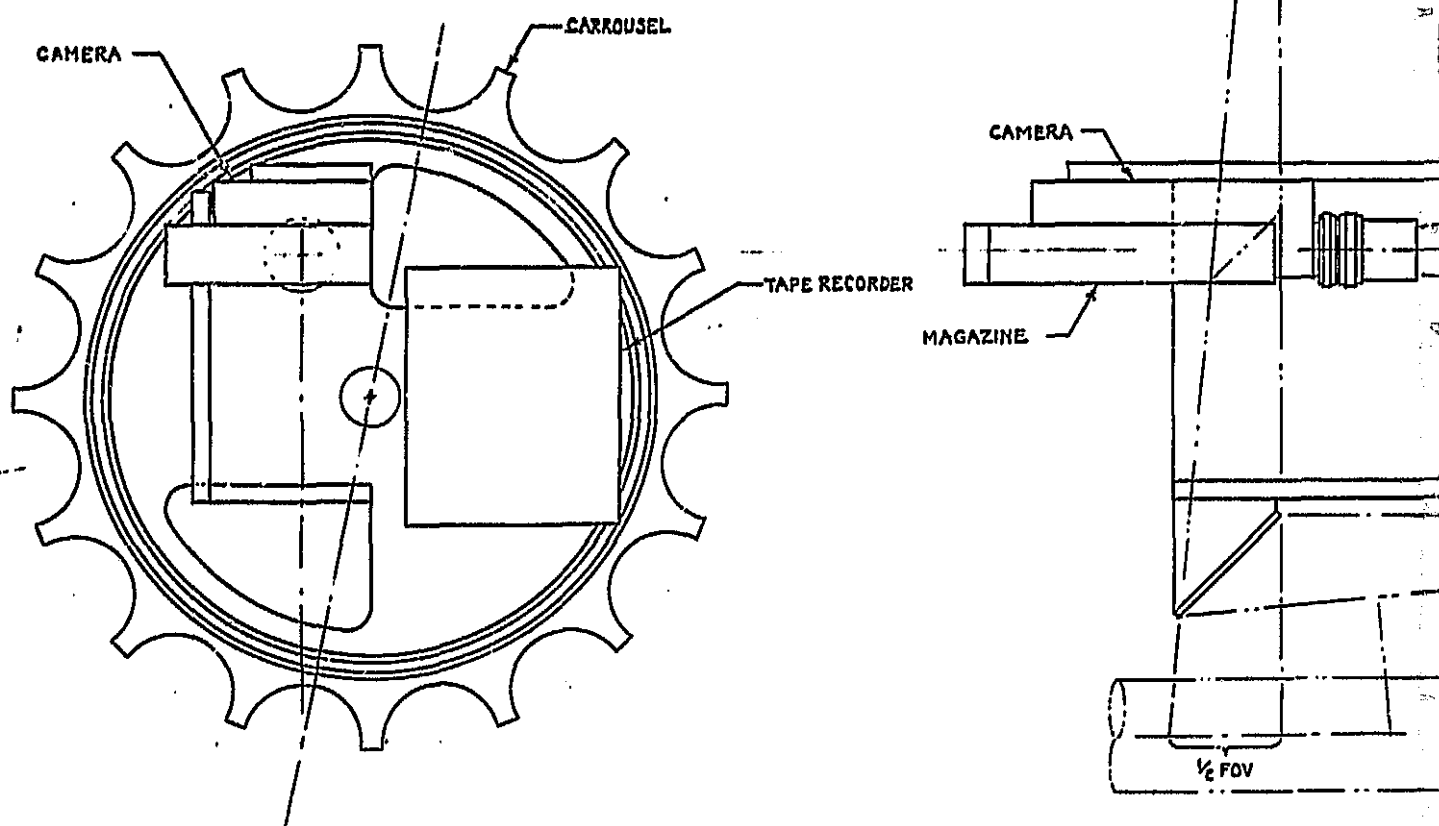


Figure 5.7 OPERATOR DISPLAY OF PARTICLE MIXING

phototransistor. As the signal varies, the position of the illuminated LED's will vary proportionately. The operator will also have visible access to confirm that homogeneous mixing has occurred. Mixing quality is measured by the agreement between the four sensor signals.

INCH SCALE

ORIGINAL PAGE IS
OF POOR QUALITY

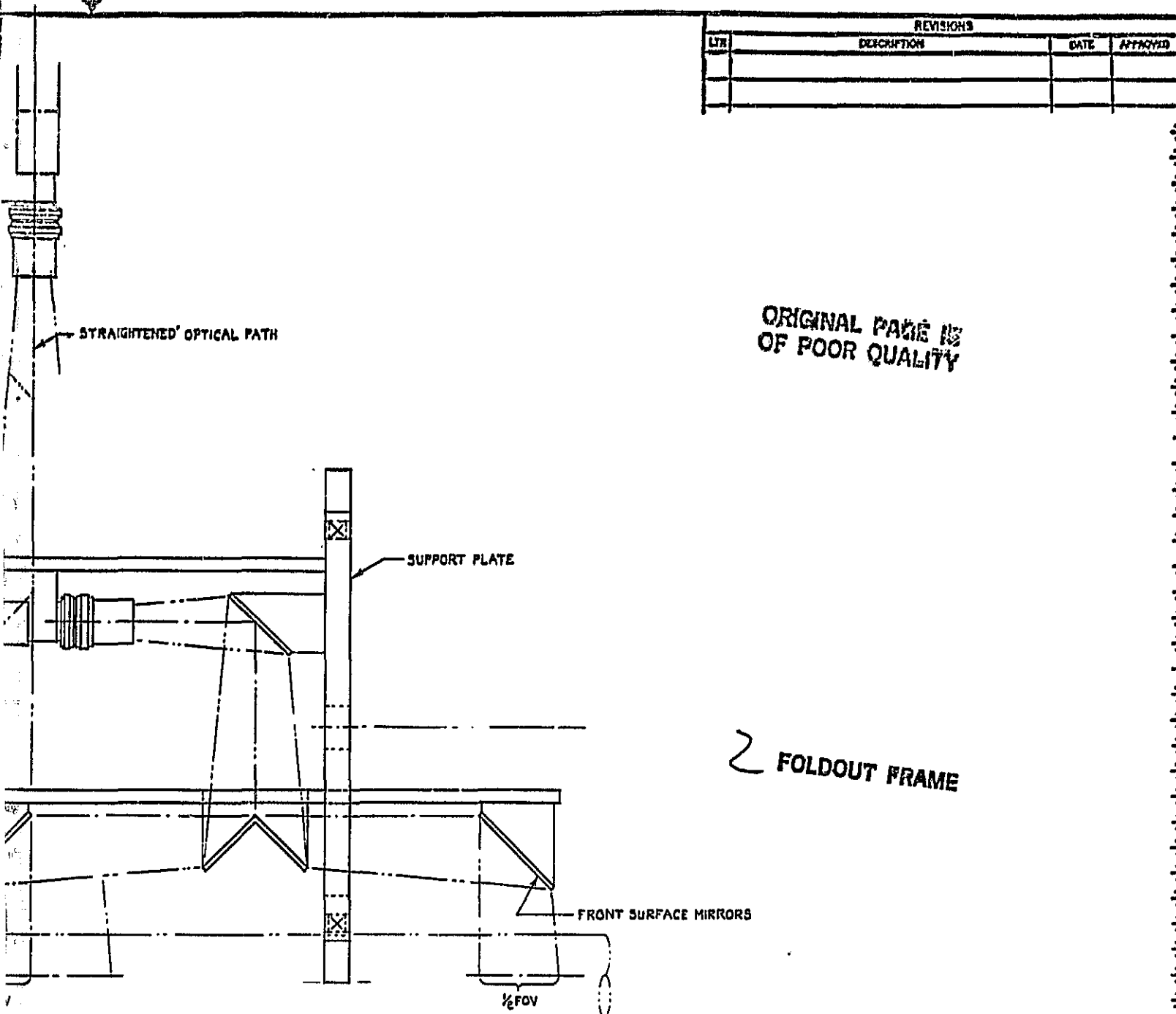


NOTES: UNLESS OTHERWISE SPECIFIED

1.

FOLDOUT FRAME

USED ON	CI NO.	NE
APPLICATION		



QTY REQD PER ASSY		FSCM NO		PART OR IDENTIFYING NO.		NOMENCLATURE OR DESCRIPTION		MATERIAL		SPEC		REV DES		ITEM NO.																															
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>UNLESS OTHERWISE SPECIFIED</p> <ol style="list-style-type: none"> DO NOT SCALE DRAWING. INTERPRET PER MIL-STD-100. DIMENSIONS ARE IN INCHES. SURFACE TEXTURE SHALL BE REMOVE BURRS AND SHARP EDGES. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING. PARENTHEetical DATA IS FOR REFERENCE ONLY. </div> <div style="width: 45%;"> <p>TOLERANCES</p> <table border="1"> <tr> <th colspan="2">ON ALL HOLE DIAMETERS</th> </tr> <tr> <td>UNDER .010</td> <td>+.003 -.002</td> </tr> <tr> <td>.010 THRU .125</td> <td>+.004 -.003</td> </tr> <tr> <td>.125 THRU .250</td> <td>+.005 -.004</td> </tr> <tr> <td>.251 THRU .500</td> <td>+.006 -.005</td> </tr> <tr> <td colspan="2">ON DECIMAL DIMENSIONS:</td> </tr> <tr> <td>XXX ± .010</td> <td></td> </tr> <tr> <td>XX ± .005</td> <td></td> </tr> <tr> <td>X ± .002</td> <td></td> </tr> <tr> <td colspan="2">ON ANGULAR DIMENSIONS:</td> </tr> <tr> <td>MACHINED ± 9°30'</td> <td></td> </tr> <tr> <td>LOCATING ± 9°30'</td> <td></td> </tr> <tr> <td>FORMED ± 5°</td> <td></td> </tr> <tr> <td colspan="2">FINISH</td> </tr> <tr> <td colspan="2">HEAT TREAT</td> </tr> </table></div> </div>																ON ALL HOLE DIAMETERS		UNDER .010	+.003 -.002	.010 THRU .125	+.004 -.003	.125 THRU .250	+.005 -.004	.251 THRU .500	+.006 -.005	ON DECIMAL DIMENSIONS:		XXX ± .010		XX ± .005		X ± .002		ON ANGULAR DIMENSIONS:		MACHINED ± 9°30'		LOCATING ± 9°30'		FORMED ± 5°		FINISH		HEAT TREAT	
ON ALL HOLE DIAMETERS																																													
UNDER .010	+.003 -.002																																												
.010 THRU .125	+.004 -.003																																												
.125 THRU .250	+.005 -.004																																												
.251 THRU .500	+.006 -.005																																												
ON DECIMAL DIMENSIONS:																																													
XXX ± .010																																													
XX ± .005																																													
X ± .002																																													
ON ANGULAR DIMENSIONS:																																													
MACHINED ± 9°30'																																													
LOCATING ± 9°30'																																													
FORMED ± 5°																																													
FINISH																																													
HEAT TREAT																																													
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>APPLICABLE SPECIFICATIONS</p> <p>THE ABOVE TRW DSSO SPECS FORM A PART OF THIS DRAWING</p> </div> <div style="width: 45%;"> <p>CONTRACT NO.</p> <p>DRAWN G. DOSA G-14-83</p> <p>CHECKED</p> <p>ENGINEER J. S. Dosa G-14-83</p> <p>OTHER APPROVALS</p> </div> <div style="width: 10%;"> <p>THE FOLLOWING EQ'S HAVE BEEN ATTACHED TO THIS PRINT</p> </div> <div style="width: 40%;"> <p>TRW</p> <p>ONE SPACE PARK • REDONDO BEACH, CALIFORNIA</p> <p>OPTICAL TRAIN</p> </div> </div>																																													
USED ON		CI NO.		NEXT ASSY		NEXT PART QTY REQD		FINAL ASSY QTY REQD		SIZE		FSCM NO		ITEM NO.																															
APPLICATION										D 11982		L 702506		SHEET 1 OF 1																															

Figure 5.6 COPSE OPTICAL SYSTEM

5.6.4 Accelerometer

The accelerometer is a Columbia Research laboratories SA-307-TX. This is a triaxial accelerometer that mounts to the carousel base plate. It is 10.3 x 7.9 x 5.41 cm (4.1 x 3.1 x 2.1 inches) and measures accelerations to 10^{-4} with an resolution of near 10^{-5} g. This device is similar to JSC device (M-GAMS). An alternate approach to a unique experiment accelerometer is to utilize the JSC package directly.

5.7 THERMAL CONTROL

Heat generated both by the combustion process and by instrumentation will be rejected via a chassis cooling fan. This device is shown in Figure 5.4, Section A-A. The fan selected is a Roton Spartan series.

5.8 ELECTRONICS

The microprocessor-controlled electronics system is shown schematically in Figure 5.8. The system is designed around a central controller which interacts with the front panel display and controls, the cooling fan, ignitor, camera, acoustic-driver, particle injection solenoid, light sources, infrared sensor, data acquisition system and the data recorder. Provision is made for registration of the carousel position and for a lock of ignitor and solenoid for tubes not in the experiment position.

5.8.1 Front Panel

Figure 5.9 details the front panel display control

PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE IS
OF POOR QUALITY

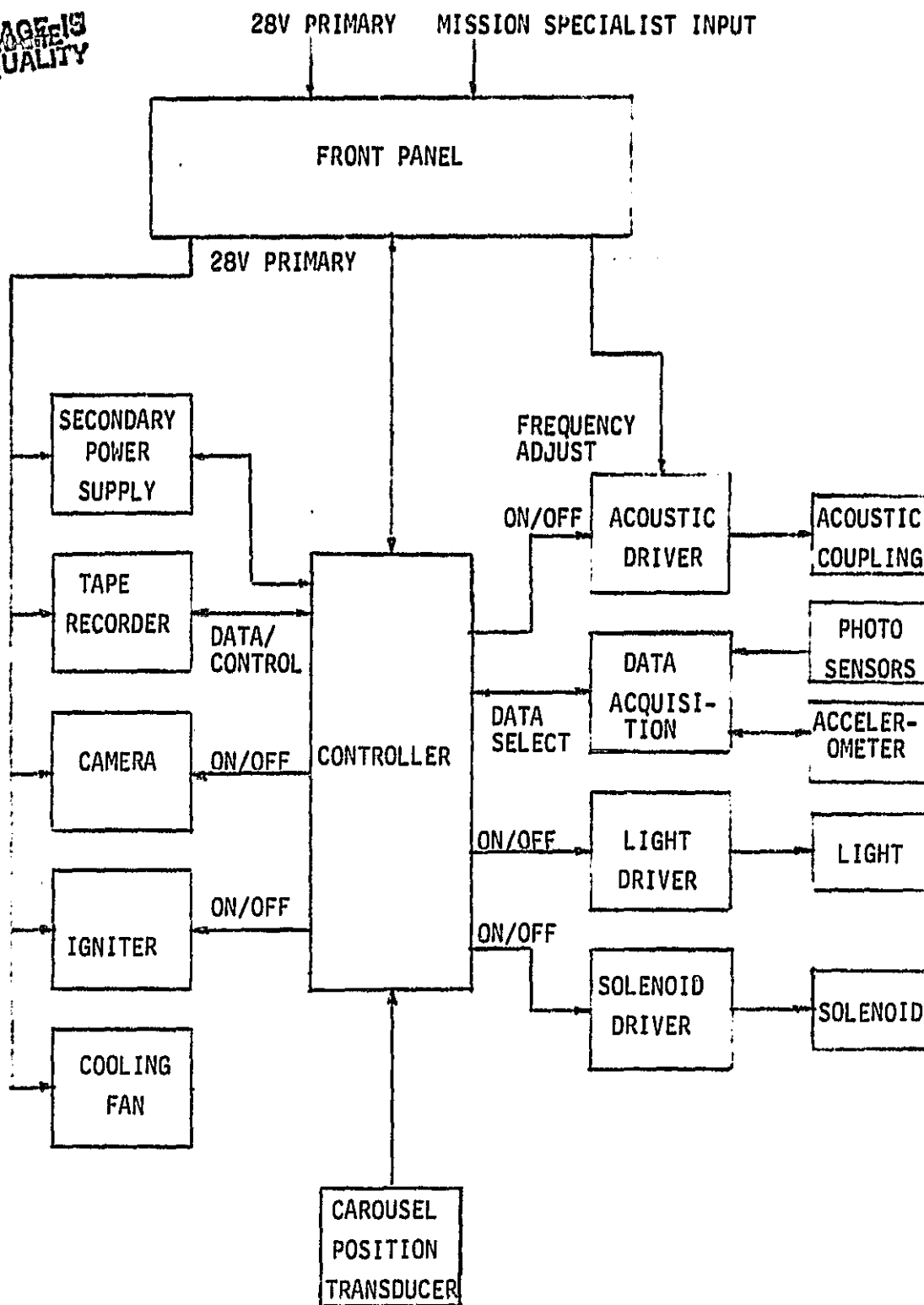


Figure 5.8 COMPOSITION EXPERIMENT ELECTRONIC BLOCK DIAGRAM

ORIGINAL PAGE IS
OF POOR QUALITY

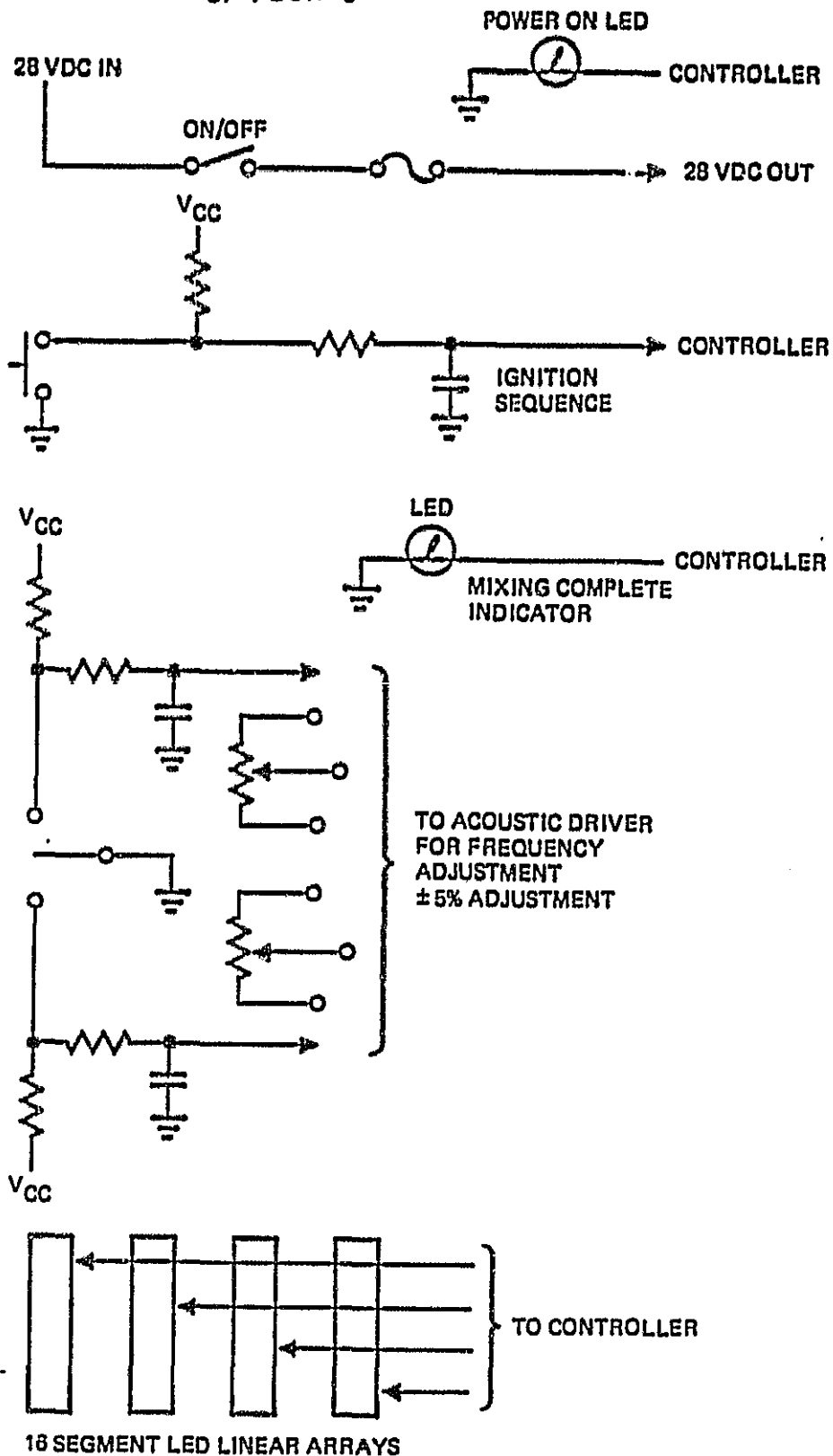


Figure 5.9 COPSE FRONT PANEL DISPLAY FUNCTIONS

electronics and Figure 5.10 shows a typical layout of the front panel. The front panel serves as the interface between the mission specialist (MS) and the experiment. A master power switch and circuit breaker with pilot light are provided with a switch to begin the experiment sequence. During normal experiment sequence the mission specialist will switch on the master power switch which will also activate the tape recorder, the homogeneity detector along with the data acquisition and controller electronics and the acoustic-driver. Trim adjustment (Fig. 5.10) is provided for the MS to tune the acoustic driver to resonance at the two mixing frequencies. A toggle switch control is available to adjust the frequency shifting and dwell at either the upper or lower resonance to facilitate tuning. Fig. 5.14 shows a typical acoustic-driver circuit and the interface to the front panel potentiometer. A homogeneity indicator which consists of four columns of sixteen LED indicators each provides the MS the degree of particle cloud homogeneity during mixing. Details of the experiment sequence on mixing and homogeneity was described in Section 5.6.3. The mixing and homogeneity indicator electronics are discussed in Section 5.8.3. Upon proper tuning of the acoustic-driver resonance, the MS will begin the mixing sequence by depressing the mixer ON/OFF switch. The mixer ON light will indicate the proper experiment sequence. The MS will visually monitor the cloud homogeneity by reading the homogeneity indicator, and to initiate the experiment by depressing the experiment ON switch. The experiment time line is discussed in Section 7.

5.8.2 CONTROLLER

The controller controls the experiment sequence in conjunction with the MS input on the front panel. It also processes the input from the infrared sensor as described in Section 5.6.3. The output to the homogeneity indicator is channeled through four (4) decoder (4-to-16 lines) to drive the

ORIGINAL PAGE IS
OF POOR QUALITY

four (4) LED columns. The controller electronics is designed around a microprocessor with its I/O and support chips. This approach provides the best compromise with respect to the functional requirements of the circuit, chip counts, size, weight, power requirements, design and manufacturing cost and overall performance capability and reliability. Figure 5.11 outlines the functional block diagram of the controller electronics. The 8048 series microprocessor family was selected based upon our prior experience on other Shuttle programs. The detail design of the controller may result in the usage of other microprocessors. The choice will depend on final design and analysis when detailed requirements are specified.

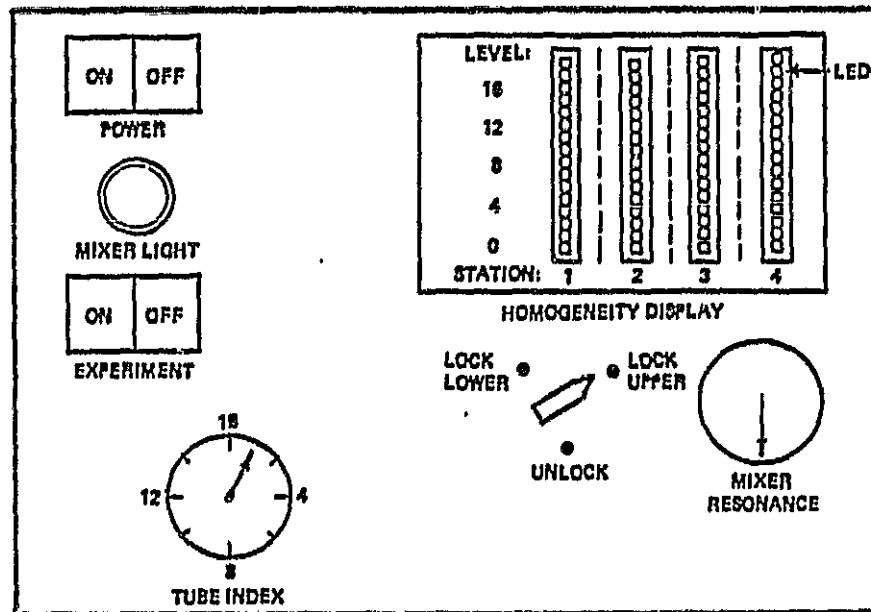


Figure 5.10 TYPICAL FRONT CONTROL PANEL

Another important function of the controller electronics is to provide the sequenced output for driving the relay circuit to turn on or off the various instruments and electronics. The various instruments and electronics is outlined in Figure 5.11. The output from the relay I/O latch will drive a series of driver (1H244) devices (Fig. 5.12). A total of sixteen relays one for

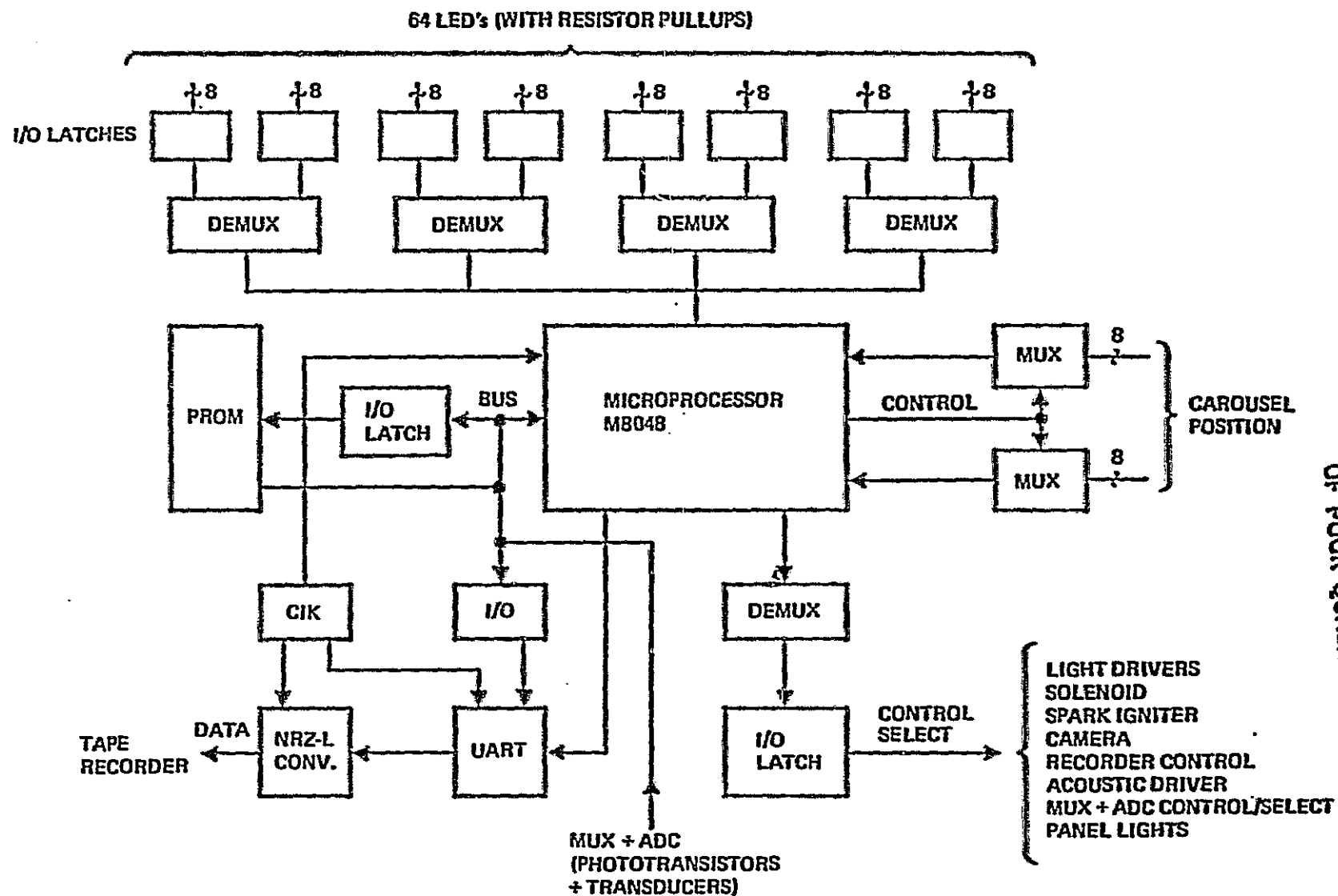

 ORIGINAL PAGE IS
OF POOR QUALITY

Figure 5.11 CONTROLLER FUNCTIONAL DIAGRAM

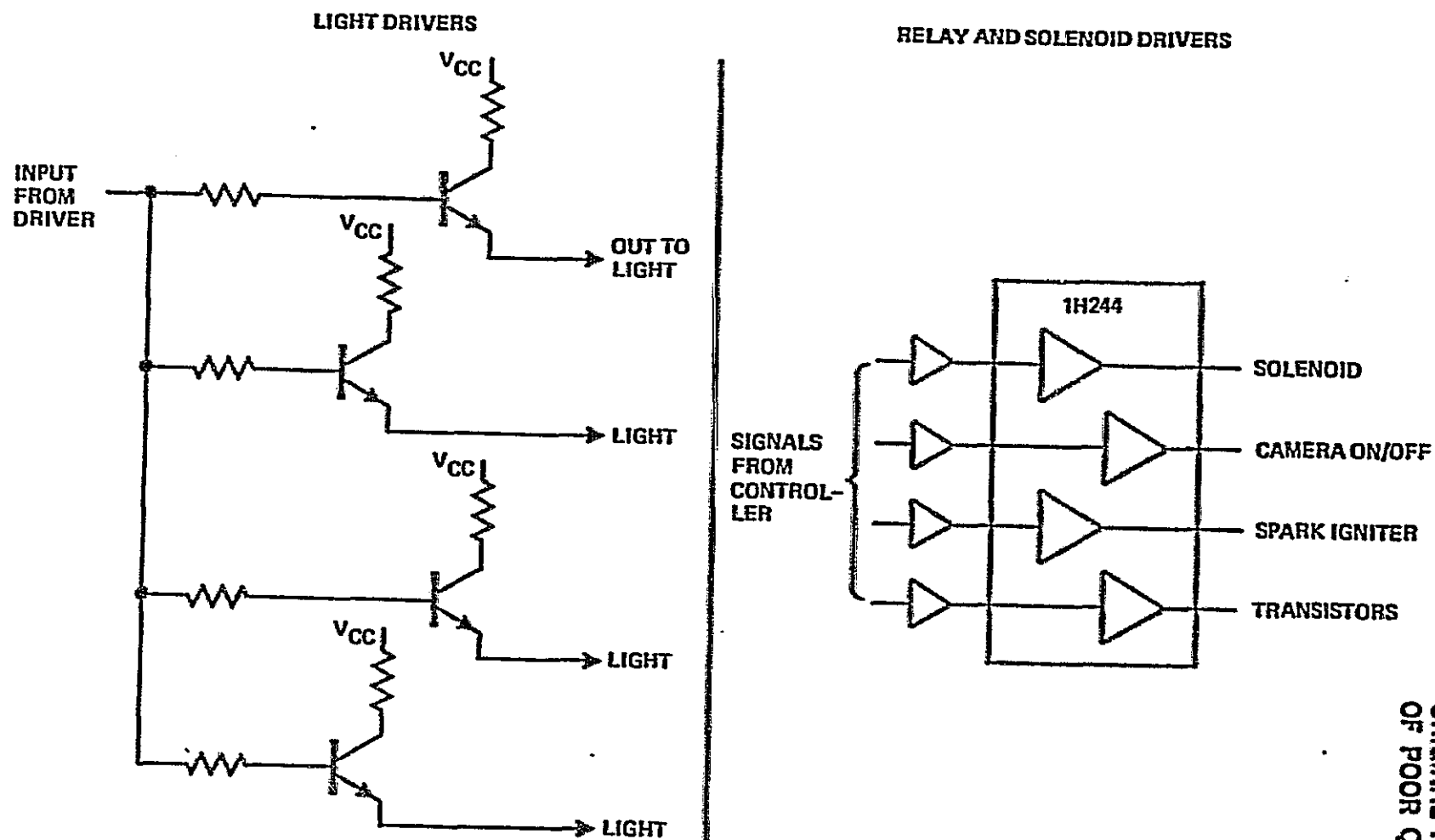


Figure 5.12 TYPICAL DRIVER OPERATION

each tube will be used to control the sixteen individual ignitors and solenoid valves. The selection of the single activated relay is dependent on the carousel position such that all other fifteen ignitors and solenoid valves not in the experiment position will be at lock-out condition to assure that improper ignition does not occur. The position of the carousel is sensed by the microprocessor through two 8-channel multiplexers. A limit switch is installed with each carousel position to signal the proper position code.

5.8.3 Data Acquisition and Recording

The data acquisition electronics interfaces with the accelerometer and the infrared sensors. The infrared sensors serve to provide the controller and the tape recorder information regarding the cloud homogeneity and the flame temperature during combustion (Sections 5.6.2 and 5.6.3). The sensor and accelerometer outputs are buffered and sampled through an analog multiplexer by a 12-bit A/D converter (Fig. 5.13). A scan rate of 250 samples per second per sensor is planned so that each sensor reading is updated every 4 milliseconds.

The digitized infrared sensor data will be processed by the controller to drive the homogeneity indicator during the mixing mode. The digitized photosensor and accelerometer information will be fed through a code converter (NRZ-L) for data storage on a digital magnetic tape recorder (Fig. 5.11). An alternate way to data storage using analog magnetic tape recorder can be realized by feeding the analog signals directly to the tape recorder with proper signal buffering.

Digital recording requires the use of the code converter and the resolution of amplitude and time is limited by the A/D resolution and scan rate. As a result, no better than 12-bit amplitude resolution and 4 millisecond time resolution can be

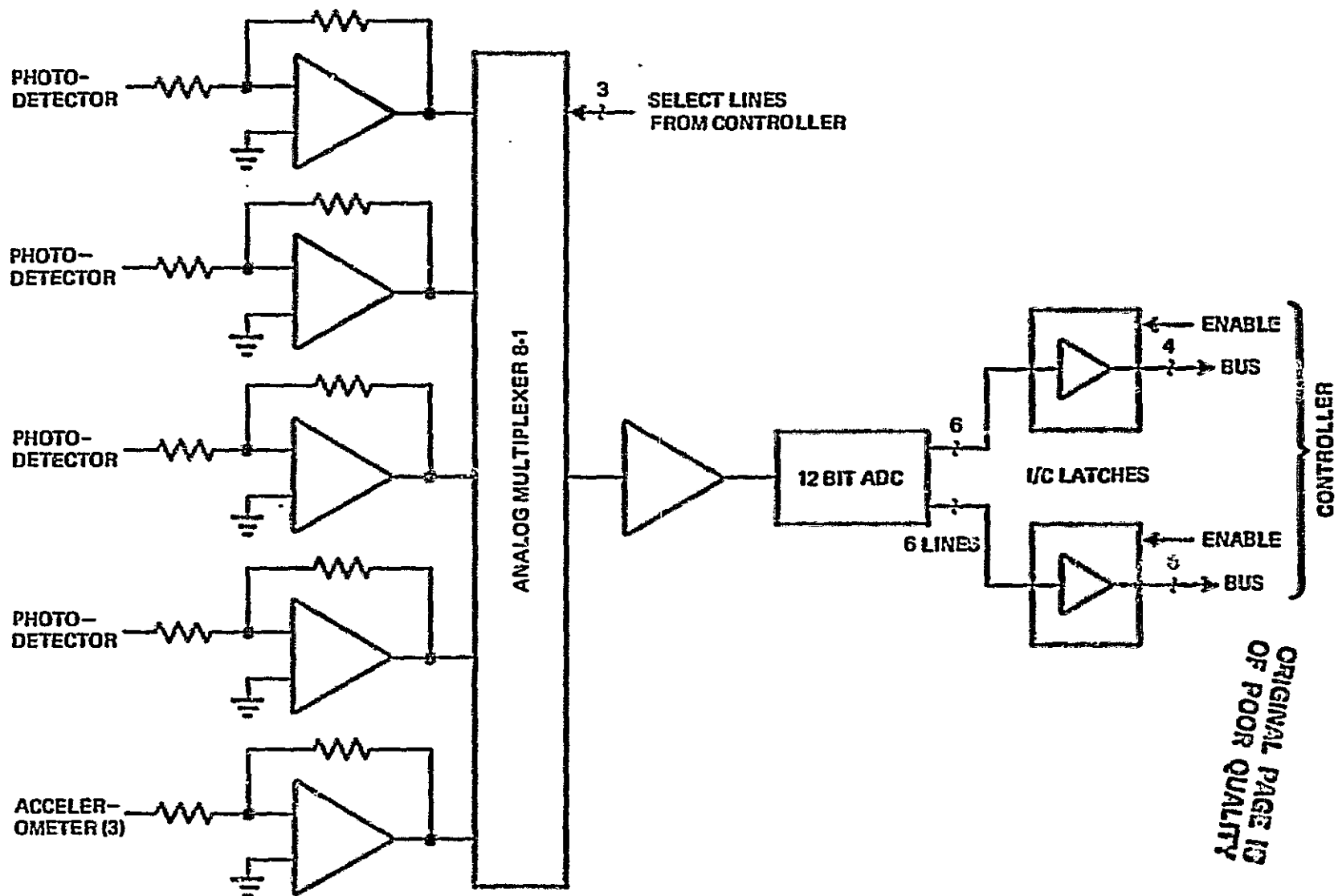


Figure 5.13 COPSE A/D CONVERT SCHEMATIC

recorded. In contrast, analogue recording will bypass the A/D mode and code conversion. Thus the amplitude and time resolution can be improved significantly. The resolution, however, will be limited by the overall system and recorder noise as well as recorder jitter.

5.8.4 Acoustic-Driver

The differing mixing approaches and tradeoffs were discussed in earlier sections. The acoustic method is selected because of its performance and ease of implementation. An acoustic mixer driving circuit is given in Fig. 5.14. Two sine wave oscillators at different frequencies will be alternately switched by the timer through the analog switch. The selected signal is fed to an output amplifier which will bring the signal power level to 25 watts rms in order to drive the acoustic horn coupled to the tube in mixing mode. The circuit will be implemented with operational amplifier circuitry and the design is estimated to present no difficulty.

5.8.5 Secondary Power Supplies

Commercially available switching DC-DC converter modules have been flown on various space and Shuttle programs. These modules, however, may not provide the best power efficiency in comparison to a custom-design circuit, but they may be the most cost effective design approach. Further analysis will be required to select the best design approach when detailed requirements are specified.

ORIGINAL PAGE IS
OF POOR QUALITY

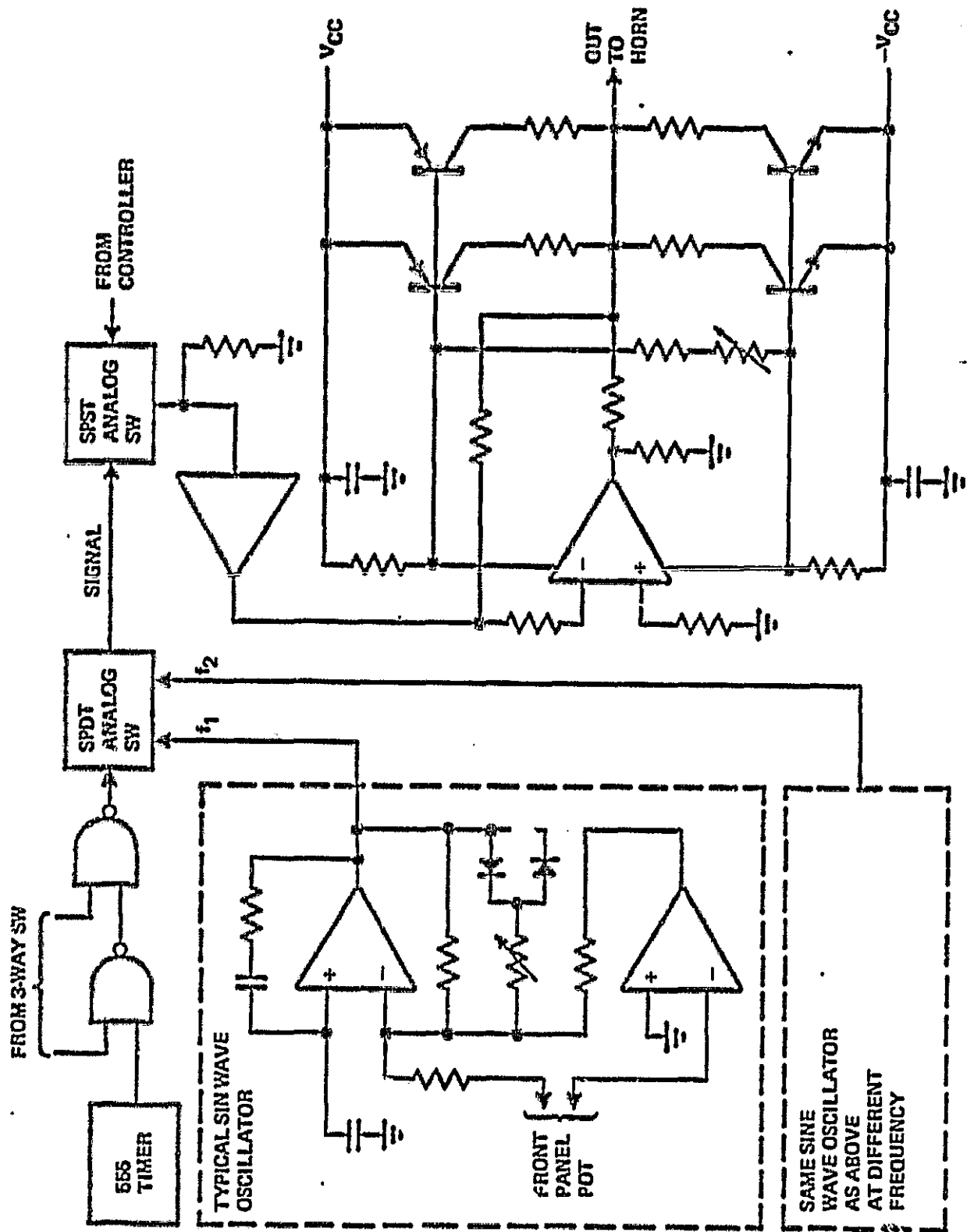


Figure 5.14 TYPICAL ACOUSTIC DRIVER CIRCUIT

5.8.6 Electromagnetic Compatibility

The combustion experiment equipment is required to operate satisfactorily not only independently, but also in conjunction with the mid-deck, other experiments, the orbiter, ground support equipment and each other. It must not be adversely affected by electromagnetic interference reaching it from external sources, in addition to meeting the EMC requirement on conductive and radiative interference derived from the Orbiter Mid-Deck/Payload Standard Interfaces Document.

The external housing of the experiment and internal electronics enclosures and wire shields will provide an adequate shield to radiative interference from external sources. In addition, these housing and shields also provide the experiment the capability to meet the radiative interference emission requirement.

Adequate fitting must be designed in the input primary power line to reject conductive interference from emitting to the source and for interference with the experiment from the source. Various equipment and electronics in the equipment are potential interference sources (both conductive and radiative). Various methods can be utilized to reduce the interference level in order to meet the EMC requirement. Table 5.4 outlines potential interference sources and the probability of interference, along with the corrective design measures to suppress or filter the interference.

These corrective design measures must be incorporated during the design and development phase of the COPSE experiment. EMC/EMI tests should also be designed and carried out as required to verify the proper performance of the equipment.

Table 5.4 COMBUSTION EXPERIMENT EMI ANALYSIS

SOURCE	EMI TYPE	INTERF. LEVEL	CORRECTIVE DESIGN PRACTICE/REMARK
1 POWER SUPPLY	CONDUCTIVE	HIGH	OUTPUT FILTER & ON-BOARD DECOUPLING & FILTER
	RADIATIVE	LOW	COMPONENT CASE SHIELDING, CASE GROUND
2 MOTORS -	CONDUCTIVE	HIGH	POWER LINE FILTER TO MOTOR, SECONDARY
COOLING FAN			POWER LINE & GROUND ISOLATION
CAMERA DRIVE	RADIATIVE	HIGH	MOTOR CASE REQUIREMENT FOR EMC, CASE GROUND,
TAPE RECORDER			TWISTED WIRES, SHIELDED WIRES
3 LATCHING	CONDUCTIVE	HIGH	SUPPLY ISOLATION
CONTACT OR	RADIATIVE	MEDIUM	DIODE SUPPRESSION
RELAY			
4 SOLENOID	CONDUCTIVE	HIGH	SUPPLY ISOLATION
	RADIATIVE	LOW	CASE GROUND
5 ACOUSTIC	CONDUCTIVE	HIGH	LINE FILTER
DRIVER	RADIATIVE	HIGH	TWISTED SHIELDED SUPPLY LINES, LOCATION OF ACOUSTIC DRIVER
			AWAY FROM MAIN ELECTRONICS. SHIELDED ELECTRONICS
6 IGNITER	CONDUCTIVE	LOW	LOW CURRENT
	RADIATIVE	LOW	LOW RISE TIME AND VOLTAGE
7 ELECTRONICS	CONDUCTIVE	MEDIUM	DECOUPLING & FILTER
	RADIATIVE	MEDIUM	SHORT LEADS, GROUND PLANE, TWISTED SUPPLY LINE

ORIGINAL PAGE 10
OF POOR QUALITY

5.9 STRUCTURES

5.9.1 Assembly Structure

The COPSE occupies four vertical locker volumes. However, it is attached at four points, two each to two single adaptor plates that are attached to the two central locker locations. This method must allow enough play in the design to compensate for any movement in the trays. The experiment must also have a structure that carries the weight of the experiment from these attachments.

The structure is shown in Figure 5.15. The casting is made of aluminum of 2.54 cm (1 inch) thickness. The adaptor plates are NASA supplied units. Figure 5.16 shows the top, front and side views of the support. There is an additional structure that supports the acoustic driver. This structure is manually manipulated to raise or lower the driver.

5.9.2 Carousel Structure

The carousel structure is shown in Figure 5.4. Main parts of this structure consist of a fixed inner portion and a rotating outer structure. Structural support is provided to the assembly structure by a central shaft. Two fixed hubs are attached to this shaft. The hubs act to carry the weight of the tubes and of other components. The components in the central volume of the experiment are attached to the hubs or are supported through them.

A hub design is shown in Figure 5.4 Section B-B. The bottom hub is a solid plate with holes for optical access etc. Only the outer hub rotates using large bearings. The tube rotation is manual and the tube is held in position by a clamp on the

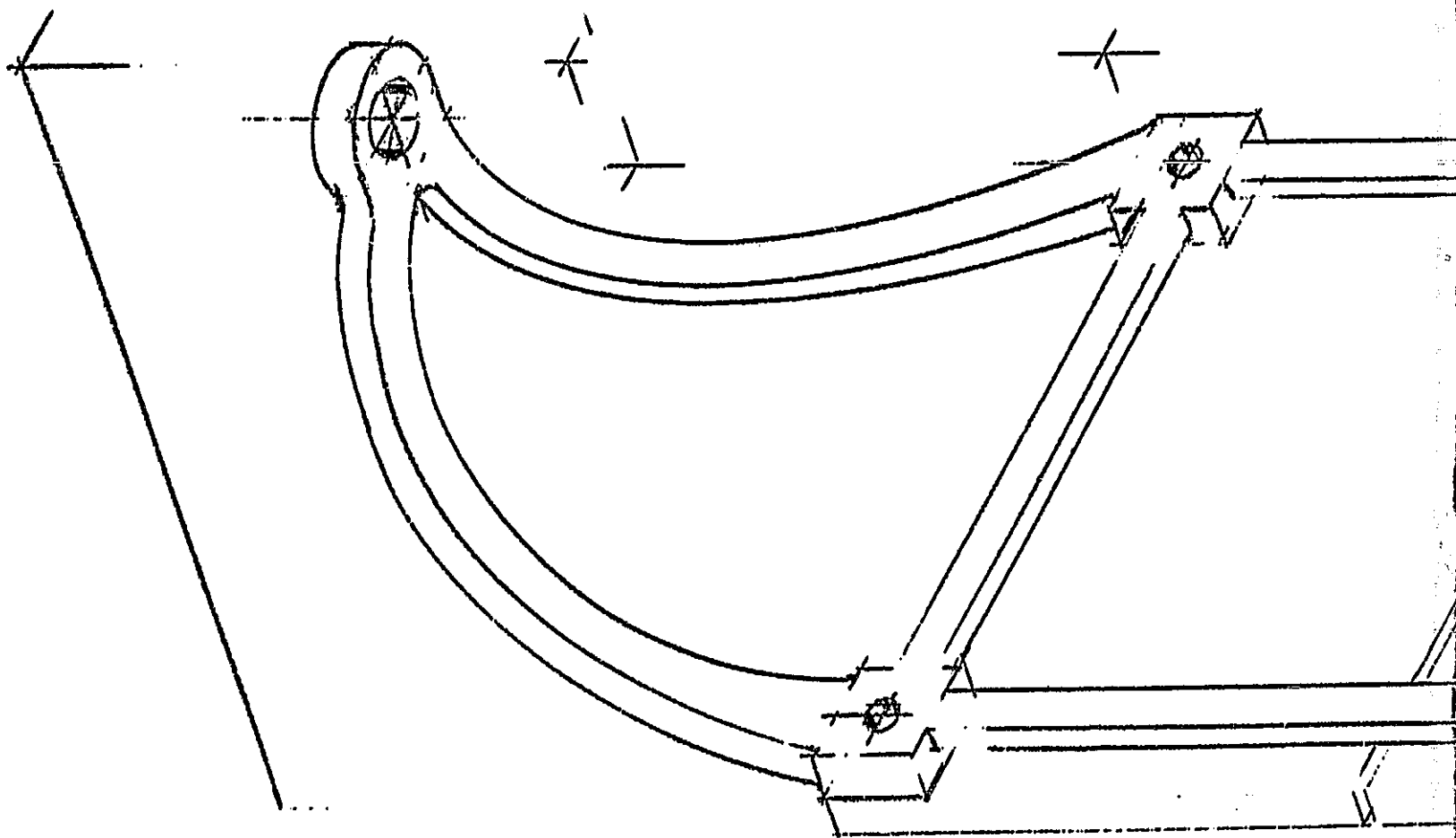
acoustic transducer. The upper hub rotates on a central bearing at the axle.

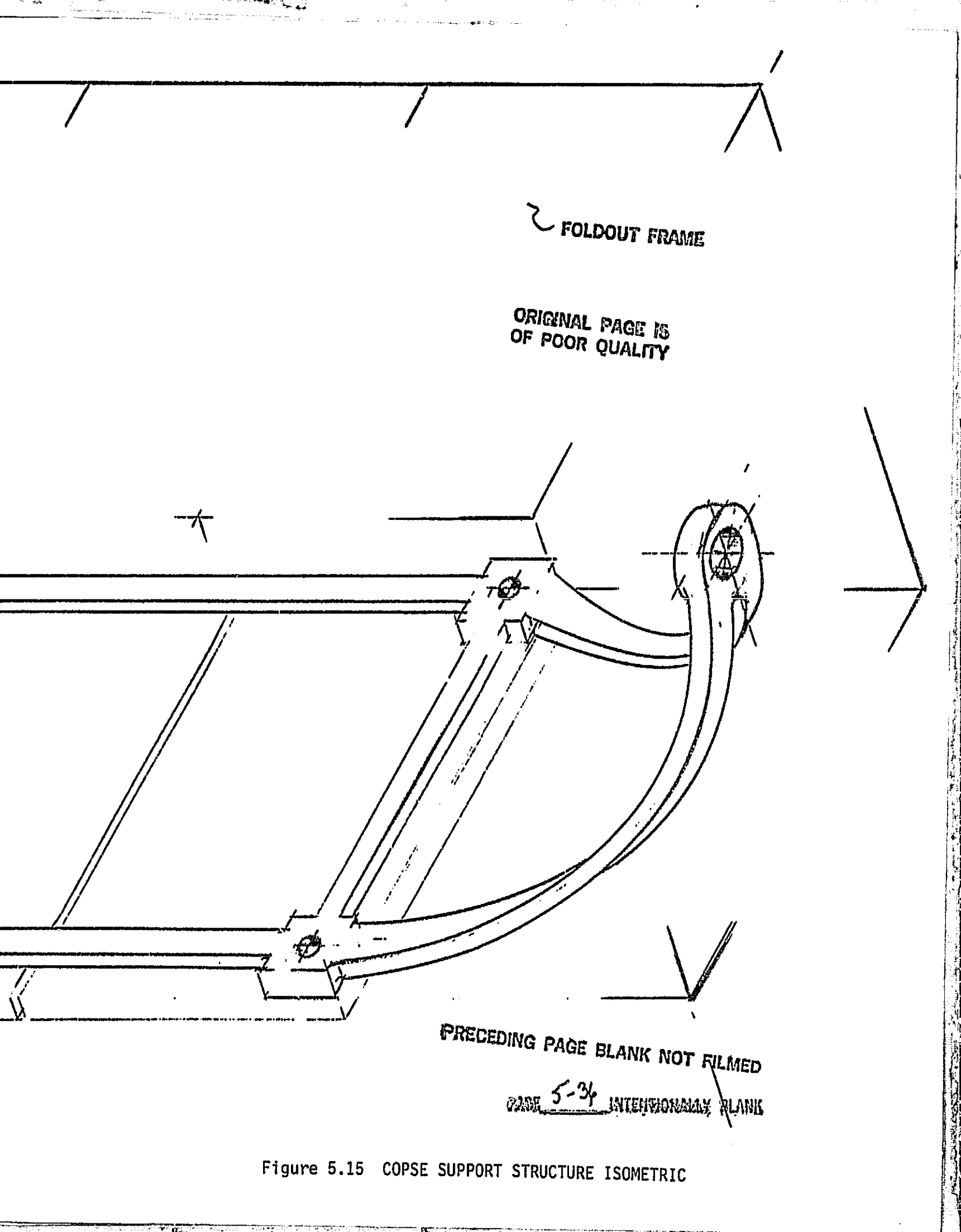
5.9.3 External Housing

The external housing is made of a honeycomb structure. It contains a door which is opened to enable rotation of the carousel; a control panel and a fan. The outer structure must be attached to the assembly structure. It can be also attached to upper and lower compartment elements.

FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY





FOLDOUT FRAME

ORIGINAL PAGE IS
OF POOR QUALITY

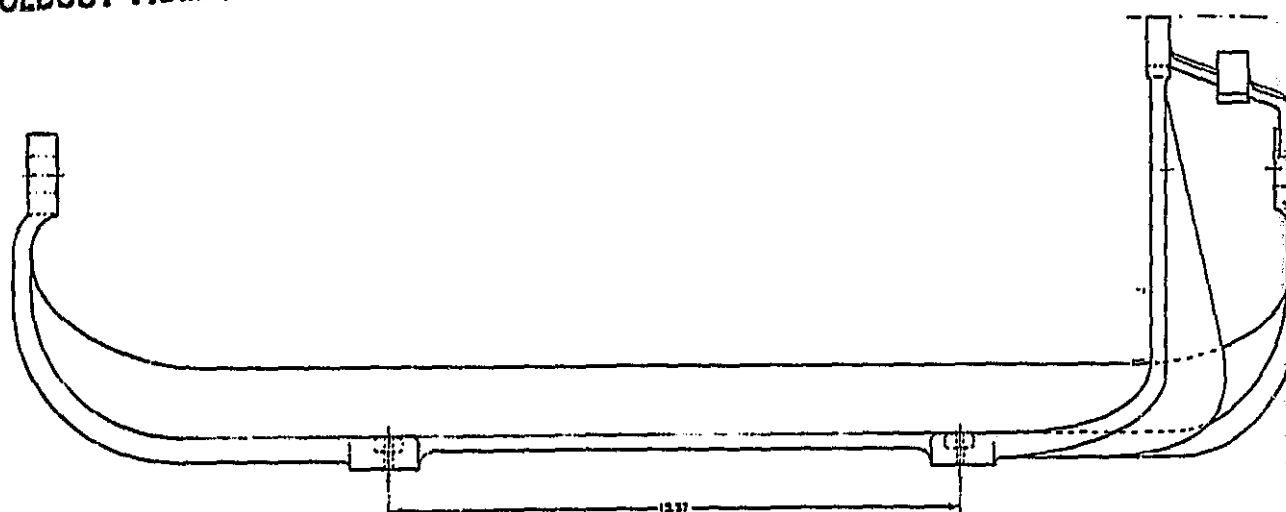
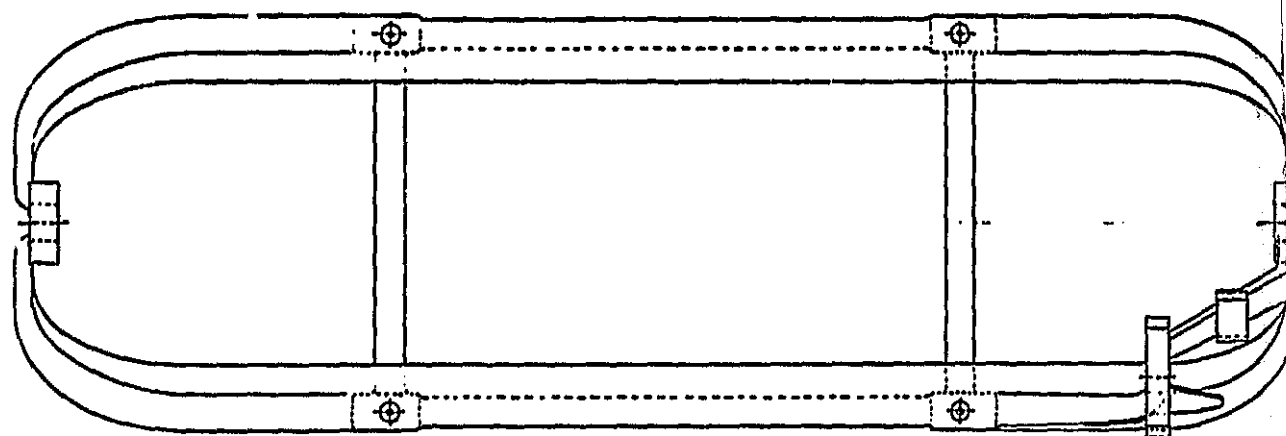
PRECEDING PAGE BLANK NOT FILMED

PAGE 5-34 INTENTIONALLY BLANK

Figure 5.15 COPSE SUPPORT STRUCTURE ISOMETRIC

ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME

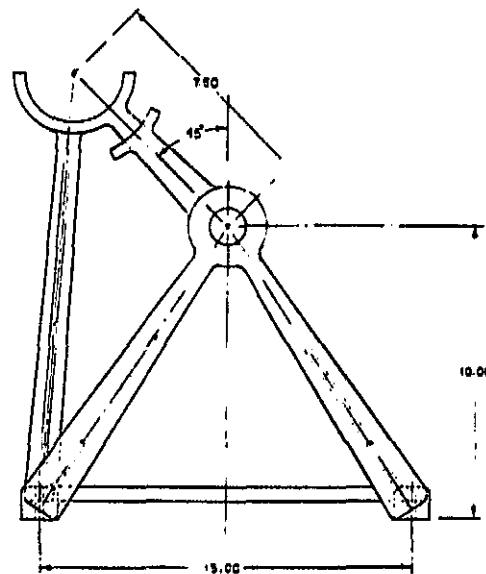
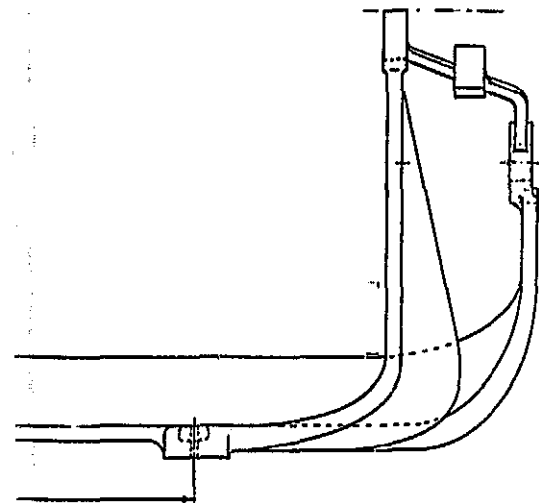
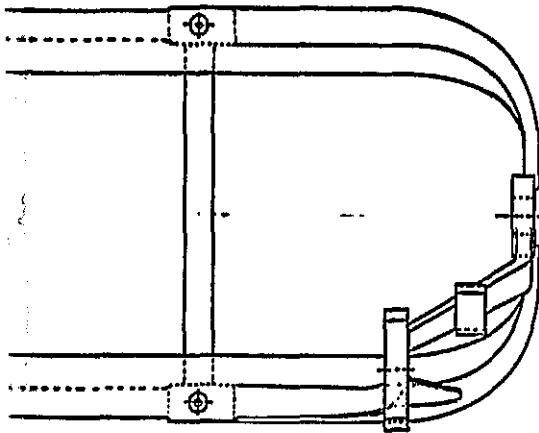


NOTE: UNLESS OTHERWISE SPECIFIED

PRECEDING PAGE BLANK NOT FILMED

ORIGINAL PAGE 10
OF POOR QUALITY

2 FOLDOUT FRAME



SUPPORT CASTING		PARTS LIST	
ITEM NO.	NAME OR DESCRIPTION	QTY	UNIT
1	CASTING	1	EA
2	WASHER	1	EA
3	NUT	1	EA
4	SCREW	1	EA
5	WASHER	1	EA
6	NUT	1	EA
7	SCREW	1	EA
8	WASHER	1	EA
9	NUT	1	EA
10	SCREW	1	EA
11	WASHER	1	EA
12	NUT	1	EA
13	SCREW	1	EA
14	WASHER	1	EA
15	NUT	1	EA
16	SCREW	1	EA
17	WASHER	1	EA
18	NUT	1	EA
19	SCREW	1	EA
20	WASHER	1	EA
21	NUT	1	EA
22	SCREW	1	EA
23	WASHER	1	EA
24	NUT	1	EA
25	SCREW	1	EA
26	WASHER	1	EA
27	NUT	1	EA
28	SCREW	1	EA
29	WASHER	1	EA
30	NUT	1	EA
31	SCREW	1	EA
32	WASHER	1	EA
33	NUT	1	EA
34	SCREW	1	EA
35	WASHER	1	EA
36	NUT	1	EA
37	SCREW	1	EA
38	WASHER	1	EA
39	NUT	1	EA
40	SCREW	1	EA
41	WASHER	1	EA
42	NUT	1	EA
43	SCREW	1	EA
44	WASHER	1	EA
45	NUT	1	EA
46	SCREW	1	EA
47	WASHER	1	EA
48	NUT	1	EA
49	SCREW	1	EA
50	WASHER	1	EA
51	NUT	1	EA
52	SCREW	1	EA
53	WASHER	1	EA
54	NUT	1	EA
55	SCREW	1	EA
56	WASHER	1	EA
57	NUT	1	EA
58	SCREW	1	EA
59	WASHER	1	EA
60	NUT	1	EA
61	SCREW	1	EA
62	WASHER	1	EA
63	NUT	1	EA
64	SCREW	1	EA
65	WASHER	1	EA
66	NUT	1	EA
67	SCREW	1	EA
68	WASHER	1	EA
69	NUT	1	EA
70	SCREW	1	EA
71	WASHER	1	EA
72	NUT	1	EA
73	SCREW	1	EA
74	WASHER	1	EA
75	NUT	1	EA
76	SCREW	1	EA
77	WASHER	1	EA
78	NUT	1	EA
79	SCREW	1	EA
80	WASHER	1	EA
81	NUT	1	EA
82	SCREW	1	EA
83	WASHER	1	EA
84	NUT	1	EA
85	SCREW	1	EA
86	WASHER	1	EA
87	NUT	1	EA
88	SCREW	1	EA
89	WASHER	1	EA
90	NUT	1	EA
91	SCREW	1	EA
92	WASHER	1	EA
93	NUT	1	EA
94	SCREW	1	EA
95	WASHER	1	EA
96	NUT	1	EA
97	SCREW	1	EA
98	WASHER	1	EA
99	NUT	1	EA
100	SCREW	1	EA

Figure 5.16 COPSE SUPPORT STRUCTURE

6.0 LAYOUT AND EQUIPMENT

The subsystems described in Section 5 have have been incorporated into an experiment which accommodates operation in the STS mid-deck. This section gives the mechanical layout, the major components, and the implications of this design in terms of weight, power and cost. The information provided in this section is taken from data in the subsystem design and details in Section 5. The design is shown to be compatible with operation in the mid-deck using four vertically arranged lockers. There are no incompatibilities with mid-deck operation that are identified using this design.

6.1 MECHANICAL LAYOUT

A layout of experimental apparatus is given in Figure 5.4. In Section A-A the width is shown to be 46.0 cm (18.12 in). The depth including the mounting plate is 53.5 cm (21.06 in) and the overall height is 113.0 cm (44.50 in) (main view). These dimensions are accommodated by 4 vertical lockers in the mid-deck area. The tube under test is at the operators right (facing the apparatus). A bracket supports the acoustic device which is centered 18 inches (46 cm) from the attachment plate. An observation window is provided for viewing the tube under test. A door in the structure is provided to allow access for rotating the tubes. The carousel is supported by a cantilever from two single plates. The camera and associated optics, the particle injector and the vent system exhaust container are mounted to structural membranes inside the carousel. The injectors are staggered to fit below the carousel plates and inside the tubes. System electronics and light sources and detectors for the mixture homogeneity device and flame propagation sensor are at fixed axial stations along the tube in the test position.

6.2 EQUIPMENT LIST

The major components of the COPSE are determined from Section 5 and from Section 6.1 and are listed in Table 6.1. The supplier is listed where procured parts are indicated. The structure and carousel assembly are fabricated specifically for the experiment. The combustion tube likewise will be a specific fabrication that will accommodate the injection and ignition requirements. In the procured parts those that were flight qualified or were proceeding toward flight qualification were used when available. Parts are to be considered representative of those required for operation.

6.3 WEIGHT ESTIMATE

The weight of the equipment has been estimated from the experiment design. Weights were obtained by the means listed below in order of increasing certainty:

- Estimates - imperfect knowledge of details, materials, etc.
- Detailed estimates based on a material selection; size etc.
- Vendor estimates based upon direct quotes or brochure values.

The weight estimate for the COPSE is given in Table 6.2. In deriving this weight we have used conservative estimates for the tubes; the structure and the electronics. The weight is shown at 116 lbs. This leaves little margin but is within the STS limit using two single adaptor plates. This weight estimate does take

Table 6.1 EQUIPMENT LIST

<u>ITEM (AMOUNT)</u>	<u>MATERIAL/TYPE</u>	<u>SUPPLIER</u>
COMBUSTION TUBE (16)	POLYCARBONATE, WALL 0.093 IN. (0.24 CM)	CUSTOM FABRICATION
STRUCTURE & CAROUSEL (N/A)	ALUMINUM	CUSTOM CASTING
CAMERA (1)	PHOTOSONICS 16-1VN	PHOTOSONICS
ELECTRONICS (N/A)	MICROPROCESSOR - BASED	CUSTOM FABRICATION
DATA RECORDER (1)	MODEL 4200	LOCKHEED
ACOUSTIC DRIVER (1)	MODEL 2425 MODIFIED WITH ALNICO MAGNET & IMPEDANCE ADAPTER	JBL
GAS BOTTLES (PARTICLE INJECTOR) (16)	MODEL 304-HDF4-75 MODIFIED TO REDUCED VOLUME	NUPRO
LIGHT SOURCES (4)	TUNGSTEN-HALOGEN 5-WATT	GTE-SYLVANIA
(VISIBLE - IR)	PHOTOTRANSISTOR, MODEL TIL-81	TEXAS INSTRUMENTS
SOLENOID VALVES (16)	MODEL 5321BA02NIAD5	ITT GENERAL CONTROLS
PRESSURE RELIEF VALVES (16)	MODEL A-4C-1 (ALUMINUM BODY)	NUPRO
MIRRORS (4)	0.08 IN. (0.20 CM) THICK	MELLES-GRIOT
TUBE END DIAPHRAGMS (32)	1 MIL MYLAR (ALUMINUM DEPOSITED)	CUSTOM FABRICATION
VENT MEMBRANES (16)	1 MIL MYLAR (ALUMINUM DEPOSITED)	CUSTOM FABRICATION
MEMBRANE SUPPORT (16)	FIBERGLASS	CUSTOM FABRICATION
HEAT REJECTION FAN	CHASSIS FAN	ROTON
IGNITION ELEMENT	ZIRONIUM FOIL	GTE-SYLVANIA
ACCELEROMETER	10^{-4} - 10^{-2} g SA 307-TX	COLUMBIA RESEARCH LAB

advantage of the reduced weight of the two single plates. However, much of this weight is gained back due to the support structure required to attach the equipment. The c.g. of the experiment has only been tentatively estimated. The values for c.g.

$$\bar{x} = 9.84 \text{ in.}$$

$$\bar{y} = 0.16$$

$$\bar{z} = 0.78$$

Final values depend upon the placement of the electronics within the assembly.

The baseline design interfaces with two lockers only. The overhang occupies two locker spaces. The 120 lb. limit can be extended by either adding an additional locker for electronics or by modifying the baseline structure to allow the suspension of the electronics or the mixer from a separate single plate.

The total weight of 116.9 pounds is considered a conservative estimate. A weight of 1.6 lbs. is allocated for each combustion tube. The analysis of Chapter 3 indicates that a tube of 0.75 pounds will have adequate strength and a significant safety margin. The potential exists for trimming 13.6 lbs for 16 tubes. The major structural components, the carousel rim and support structure casting are designed with no trimming. We estimate that these parts have a combined weight of 21.2 lbs. An estimated 25% (5.3 lbs.) can be saved by designing these parts using stress analysis. Substitution of titanium for aluminum can result in further weight decrease of approximately four pounds.

A total weight savings potential of 22.1 lbs exists. This is an additional margin of 18% of the 120 lb. limit. This coupled with the indicated margin gives a 20% total weight margin.

Table 6.2 POROUS SOLIDS EXPERIMENT
WEIGHT ESTIMATION

ITEM	WEIGHT		SOURCE
	(kg)	(lbs)	
CONDUCTION TUBE, 1.60 x 16	11.64	25.60	DETAILED ESTIMATION
RIM, 1.92 x 2 + 0.19 SPOKES	1.83	4.03	DETAILED ESTIMATION
CENTRAL CAROUSEL TUBE (1 1/2 x 0.065 x 36" LG)	1.02	2.24	DETAILED ESTIMATION
MAIN SUPPORT PLATE (ALUMINUM) 11" x 0.75"	2.10	4.63	DETAILED ESTIMATION
CAMERA	1.70	3.75	VENDOR
ELECTRONICS	2.27	5.00	DETAILED ESTIMATION
DATA RECORDER	2.95	6.50	VENDOR
ACCELEROMETER (1)	0.34	0.75	VENDOR
MIRRORS 4 x 0.08" THICK	0.15	0.32	ESTIMATION
ACOUSTIC DRIVER	4.09	9.00	VENDOR
LIGHTS (4)	0.28	0.62	VENDOR
DETECTORS (4)	0.11	0.24	ESTIMATION
INJECTOR SYSTEM (16)	2.73	6.00	DETAILED ESTIMATION
EXHAUST SYSTEM (16)	1.14	2.50	DETAILED ESTIMATION
SINGLE PLATE (FMP) (2)	2.27	5.00	NASA
ENCLOSURE (HONEYCOMB)	11.15	24.54	DETAILED ESTIMATION
SUPPORT STRUCTURE CASTING	6.90	15.17	DETAILED ESTIMATION
FAN	0.45	1.00	VENDOR
TOTAL	53.12	116.89	

6.4 ELECTRICAL REQUIREMENTS

The power requirements for the COPSE have been estimated to determine the initial compatibility with the mid-deck supplied power.

ORIGINAL PAGE IS
OF POOR QUALITY

The electrical power requirements are given in Table 6.3. The electronics design (Section 5.8) utilizes stabilizing power supplies in consideration of the STS mid-deck variation from 23 VDC to 32 VDC. In our power estimates we assume that such stabilization is not required. Such stabilization will introduce a 30% increase into the power requirements.

Table 6.3 COPSE IN-FLIGHT POWER REQUIREMENTS

a) Mixing Cycle	10 sec - 2 Minutes
Component	Power (watts)
fan (28VDC)	35
Logic Controls and Data Recording	55
Light Driver	50
Mixer	70
Total	210 watts
b) Experiment Operation	(10 seconds)
Fan	35
Logic, Controls, and Data Recording	35
Camera	170
Ignition (momentary)	10
Total	250 watts

The power is summarized for the two sequential operations. The mixing phase from 0-2 minutes utilizes about 200 watts.

The experiment phase of about 10 seconds requires 250 watts with the ignitor being only a momentary pulse. These requirements are both within the specification of a single power

bus from the mid-deck. The total energy consumption is 7.36 watt hours per experiment or 117.6 watt hours for 16 experiments. The total power requirement for this experiment is nominal.

7.0 MISSION OPERATION

The experiment design implies a definite mission timeline. This mission timeline has allocations for crew time and gives a preliminary indication of other requirements on STS. The operating time, crew time and other requirements are discussed in this section.

7.1 CREW INTERACTION

The COPSE design is developed using 16 tubes. The crewman is required to rotate each tube sequentially into the experiment position, latch the carousel and close the access door. He will initiate the mixing sequence and perform any necessary trimming of the acoustic driver oscillators. Upon indication of satisfactory mixing as displayed by the bar LED display or after a fixed time has elapsed the operator will initiate the experiment sequence. During the test period, the operator will visually observe the ignition and flame propagation using the window provided. Visual observations include:

- Particle injection
- Mixing behavior
- Effects of signal (resonance) trimming
- Wall adhesion of particles
- Particle-particle agglomeration
- Ignitor appearance and flame front development

- Propagating flame steadiness and symmetry.

ORIGINAL PAGE IS
OF POOR QUALITY

7.2 TIME LINE

The time line is given in Table 7.1. The elapsed time for 1 experiment is 4 minutes, thus 64 minutes are required for the entire test series. This time need not be continuous so that tests may be run singly or in groups. A stable level of 10^{-4} g is required for proper operation. The pressure should be at 14.7 psi and the experiment operated before any EVA.

Table 7.1 TIMELINE FOR CARRYING OUT
COMBUSTION TUBE EXPERIMENT

EVENT NUMBER	1	2	3	4	5	6	7	8
TIME	20 SEC	10 SEC	20 SEC	1 MIN	20 SEC	20 SEC	1 MIN	20 SEC
FUNCTION	LOCK TUBE IN POSITION	MIXING 1	MIXING 1 TUBE MIXER	MIXING 2	TURBULENCE DECAY	INITIATE TEST	RECORD OBSERVATIONS	TERMINATE EXPERIMENT
DESCRIPTION	<ul style="list-style-type: none"> • TUBE ROTATED IN TEST POSITION • CONTACTS MADE WITH IGNITION ELECTRODES • ACOUSTIC DRIVER LATCHED TO TUBE END 	<ul style="list-style-type: none"> • POWER ON • BEGIN DATA RECORDING • HOMOGENEITY DETECTOR ON • ADJUST ACOUSTIC MIXER FOR RESONANCE 	<ul style="list-style-type: none"> • OPERATE SOLENOID VALVE • PULSE AIR JET INTO TUBE • VERIFY PARTICLE INJECTION 	<ul style="list-style-type: none"> • OPERATE ACOUSTIC MIXER • OBSERVE LED DISPLAY OF HOMOGENEITY DETECTOR • TAPE DRIVE 	<ul style="list-style-type: none"> • STOP GENTLE MIXING & WAIT FOR TURBULENCE TO DECAY 	<ul style="list-style-type: none"> • EXPERIMENT ON • CAMERA ON • LIGHTS OFF • IGNITOR FIRED • DETECTORS REMAIN ACTIVATED 	<ul style="list-style-type: none"> • WRITE SUMMARY OF VISUAL OBSERVATIONS DURING TEST 	<ul style="list-style-type: none"> • VERIFY FLAME-OUT • UNLOCK TUBE • ROTATE NEXT TUBE INTO TEST POSITION

8.0 EXPERIMENT SAFETY

The Combustion of Porous Solids Experiment has been analyzed for safety hazards. Payload Safety Matrix was prepared and Payload hazard reports made for each hazard identified. Following this analysis a Phase "O" Safety Review was conducted for this experiment at JSC. The Safety Matrix and the hazard reports were ammended in accord with the results of this review. These results together with the comments from this review are presented in Appendix 10.

The Phase "O" safety Review resulted in redefining of the experiment concept. There was a strong indication at the JSC review that the experiment should, as far as possible, consist of self-contained tubes in which the particles and combustion gases would be contained. Such a self-contained experiment will allow the STS safety requirements to be met. Specific actions that have been performed as a result of the Phase "O" briefing include:

- The combustion tube is designed so that all particles and gases are contained totally within the tube from lift-off to landing.
- Individual pressure bottles, one for each experiment tube have replaced the common pressure bottle of the conceptual design. The energy of each bottle will be only 10 joules.
- Electrical contacts to each tube will be hard-wired to eliminate any high voltage contacts within the system.
- The particles will be in steel tubes. This will eliminate any breakage of the particle containers and

subsequent dispersal of particles in the STS.

Some of the safety issues were not resolved by this study. Many issues exist that can be resolved only after the specific experiment complement that will be flown is known. Specific unresolved issues follow:

- The potential for all tubes being broken and all particles be mixed in the experiment volume must be assessed. If such an occurrence is possible the potential for a flammable mixture occurring should be assessed.
- A handling procedure for tubes that contain unignited particles is required if the particle-air mixture represents any flammability hazard, such as tube breakage.
- The combustion gas that will be present in each tube following combustion should be estimated using the best combustion model available. The potential toxicity problem will determine the number of inhibits required of each tube.
- The potential for hazard in an emergency landing situation may exist if differential pressures on the elastomer materials are too great. Further analysis as to the effect of a 4-8 pound differential must be carried out during the detailed design phase.

9.0 EXPERIMENT STATUS

The preliminary design of the COPSE has shown that it can be accommodated in the mid-decker locker region of STS.

This design follows from the science requirements derived from discussions with Dr. Berlad during the Apparatus Analysis Phase. The final design has a 16 tube carousel limited by the available volume in mid-deck and utilizes the power of one mid-deck bus.

The experiment as configured has the following properties:

- It is accommodated in mid-deck using the volume of four lockers.
- It can be accommodated with modified structures in a galley location.
- It can be accommodated in a spacelab rack or in a simplified combustion facility-type structure.

The design does not require large amounts of cooling and can be operated within the design limits imposed using one power bus.

9.1 EXPERIMENT REQUIREMENTS

The design in this report meets the major science requirements that were established in our initial review with one known design exception and one STS induced exception. Table 9.1 shows the major requirements vs experiment capabilities.

The significant design exception is that the pressure

Table 9.1 COPSE REQUIREMENTS VS EXPERIMENT
DESIGN CAPABILITIES

REQUIREMENT	EXPERIMENT DESIGN CAPABILITY
<u>PRE-TEST</u>	
1. COMBUSTION TUBE LENGTH 100 CM DIAMETER 5 ± 0.2 CM	LENGTH 81 CM DIAMETER 5.6 CM - 5.0 CM CAN BE MET
2. IGNITION SECTION LENGTH 6.0 CM DIAMETER 6.0 CM	MEETS REQUIREMENTS
3. OXIDIZER DRY AIR	FILL WITH DRY AIR; MID-DECK GAS COMPOSITION 25.9% O ₂ . EXPERIMENT DESIGN DOES NOT PRECLUDE SOME EXCHANGE OF TUBE O ₂ (21%) WITH CABIN AIR.
4. EXPERIMENT NUMBER UP TO 100 EXPERIMENTS	16 EXPERIMENTS PER FLIGHT
5. PARTICLE TO BE MAINTAINED DRY	MEETS REQUIREMENTS; STORAGE OF N ₂
6. PRESSURE AMBIENT	OPERATE WITH STS PRESSURE 1×10^5 PA (14.7 PSI)
7. TEMPERATURE AMBIENT $25 \pm 5^\circ\text{C}$	OPERATE AT AMBIENT STS TEMPERATURE
8. G LEVEL 10^{-4} G	OPERATE AT STABLE STS G LEVEL
9. PARTICLE UNIFORMITY OVER ACTIVE VOLUME $\pm 5\%$	<ul style="list-style-type: none"> • MIXER CONCEPT MUST BE VERIFIED • DETECTOR MEASUREMENT OVER DEFINED CONCENTRATION RANGE
10. G LEVEL DURING EXPERIMENT	<ul style="list-style-type: none"> • ACCELEROMETER MEASURES G LEVEL 10^{-4} G $\pm 5 \times 10^{-5}$ G
11. TURBULENCE DECAY	<ul style="list-style-type: none"> • TIME LAPSE DETERMINED BY ANALYSIS
12. PRE-EXPERIMENT CONDITION VERIFICATION	<ul style="list-style-type: none"> • ASSUME STS PRESSURE AND TEMPERATURE DATA AVAILABLE
<u>TEST OPERATIONS</u>	
13. IGNITION SOURCE 1-2J	<ul style="list-style-type: none"> • Zr WIRE GIVES 226J
14. FLAME SPEED 5-100 CM/SEC	<ul style="list-style-type: none"> • DATA RATE 1000/SEC FOR DETECTORS

ORIGINAL PAGE IS
OF POOR QUALITY

Table 9.1 COPSE REQUIREMENTS VS EXPERIMENT
DESIGN CAPABILITIES (cont.)

REQUIREMENT	EXPERIMENT DESIGN CAPABILITY
15. FLAME SHAPE - 0.1 MM RESOLUTION - IGNITION VISUALIZATION 16. TUBE PRESSURE ± 1 TORR 17. ON BOARD DISPLAY	<ul style="list-style-type: none"> • CAMERA 100 FRAMES/SEC - GIVES 1 CM RESOLUTION AT MAX SPEED • BY CAMERA FOV DESIGN • RELIEF VALVE ONLY <ul style="list-style-type: none"> - OPENS WHEN PRESSURE IS 259 TORR (5 PSI) ABOVE PRESSURE CONTROL PANEL PROVIDED
<u>POST TEST</u>	
18. VERIFY FLAME OUT	VISUAL OBSERVATION
19. VENTING SHUT OFF AND SEAL TUBE	EACH TUBE IS A CLOSED SYSTEM
20. RETURN FIRED TUBES FOR ANALYSIS	ALL EXPERIMENT HARDWARE IS INTACT

ORIGINAL PAGE IS
OF POOR QUALITY

measurement during the experiment has been excluded. This exclusion was a conscious design decision. The closed tube design requires an individual pressure transducer for each tube. This in turn requires sixteen pressure transducers. The inclusion of these transducers will complicate the design.

- The available space requires a small lightweight device. Such devices are high cost items and there may not be space to include this.
- The electronics will be complicated by the additional requirements.

The pressure relief valves do provide a single point indication of five pounds over pressure as well as providing a safety factor.

The oxygen concentration at 14.7 psi in the mid-deck is 25.9% not the normal 21% at atmosphere. The tube is design to be closed but not leak tight over a long period of time. We expect that there will be only a small or negligible change in tube pressure after lift-off. However, the requirement for 21% O₂ (dry air) cannot be guaranteed without design change and strict leak testing of the tubes.

9.2 TECHNICAL TESTING

The design reflects our best estimate of the materials used. In several cases development testing of design approaches are indicated. All elastomer materials defined

- The bellows
- The tube diaphragm

- The particle cartridge diaphragm

should be evaluated for strength on the one hand and for bursting ability on the other.

Test Diaphragm The capability to withstand 5 psi over pressure; launch environments should be evaluated. The permeability to both oxygen and expected combustion gases must also be determined

Particle Cannister Diaphragm The ability to withstand launch environments and the reliability of rupture upon exposure to air pressure require evaluation.

Bellows The ability to build leak tight devices and the pressure limit require evaluation.

Tube Saturating The occlusion of particles to the tube walls represents an experiment problem in accurately determining the homogeneity and in verifying that all particles are in the gas phase and available for combustion. This problem has been left for determination by LeRC and by Prof. Berlad. The choice of the tube material may depend upon the occlusion properties.

9.3 DESIGN ISSUES

The design as presented should be evaluated in several areas in the next detailed design phase.

Thermal Analysis of Vent The venting system is based upon two components.

- A Ni heat sink
- A mylar bellows

Our analysis suggests that the internal sinks should remove sufficient heat from the combustion gases such that only a one liter capacity for the bellows is required. A more detailed analysis is indicated to evaluate whether a more massive heat sink is required or whether the bellows requires a greater volume. The present configuration is probably adequate.

Limited Field-of-View The camera split image provides a view of the ignition region and of the tube center. This should be evaluated to gain the most scientific data from the camera usage. If the ignitor view is not required two tube views can be obtained.

Enclosure The enclosure at present surrounds the experiment and contains any particles. An additional requirements on the enclosure should be evaluated before detailed design.

9.4 SAFETY CONSTRAINTS

The safety operation of this experiment may constrain the design. We have made a design that incorporates the safety factors as far as we understand them. The mechanical design and electronic considerations are made based upon our understanding of Phase "O" results.

10.0 REFERENCES

1. Berlad, A.L., and Kellog, J., "Combustion of Porous Solids at Reduced Gravity Conditions", (NASA Contractor Report 3197, 1979).
2. "Analysis of the Preliminary Design of a Zero-Gravity Combustion Facility for Spacelab", NASA CR-167843 (1982).
3. Orbit Mid-Deck Payload Provisions Handbook, Rev. B, JSC-16536 (September 1982).
4. Orbiter Mid-Deck/Payload Standard Interfaces, 30 Nov. '82.
5. Krieth, F. (1973), "Principles of Heat Transfer", Third Edition, Intext Publishers, New York.
6. Culick, F.E.C., (1974), "T-Burner Testing of Metallized Solid Propellants", (Air Force Report AFRPL-TR-74-28), pp. 213-239.

**APPARATUS ANALYSIS AND PRELIMINARY
DESIGN OF LOW GRAVITY
POROUS SOLIDS EXPERIMENT
FOR STS ORBITER MID-DECK
APPENDICES**

NAS 3-23254

NASA/Lewis Research Center

Submitted by

Applied Technology Division

TRW - S&TG

October 1983

APPENDICES

The Appendices are working notes used to derive results given in the bulk of the report.

The appendices are:

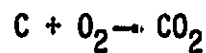
- Appendix 1. Heat Sink Mass Selection
- Appendix 2. Energy of Gas Storage/Mass/ Complication Comparison
- Appendix 3. Mechanical Mixer Performance Analysis
- Appendix 4. Acoustic Mixer Program Selection
- Appendix 5. Acoustic Loss Calculation
- Appendix 6. Aerodynamic Mixer Design Analysis
- Appendix 7. Particle Size Scaling Analysis
- Appendix 8. Optical Scattering by Fuel Particles, Sensor Output Interpretation
- Appendix 9. Laboratory Equipment Operating Instructions and Parts List
- Appendix 10. Safety Hazard Reports
- Appendix 11. Summary of Discussions at Final Briefing (8/10/83)

APPENDIX 1

Heat Sink Selection

1) What quantity of heat should be extracted from the exhaust?

Combustion model:

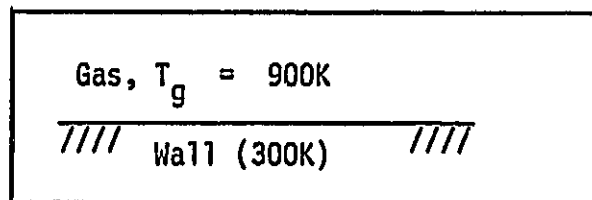


with O_2 limited to 0.017 gmole

gas mole ratio = 1 (# of moles of gas is the same before and after reaction)

Heat release: 94 Kcal/gmole $O_2 \Rightarrow 1.6 \text{ Kcal} = 6700 \text{ J}$

How much heat will be lost to the wall during flame propagation time ($\sim 1/2 \text{ S}$)? Is it a significant fraction of heat evolved?



- assumed heat transfer arrangement for 1st order calculation.

$$\frac{h_c^{-2} a \theta}{K_s} = \frac{(5 \text{ w/m}^2\text{K})^2 \cdot 1.28 \times 10^{-7} \text{ m}^2/\text{sec}}{(0.193 \text{ w/MK})}$$

$$\frac{h_c L}{K_s} = \frac{(5 \text{ w/m}^2\text{K}) \cdot 1.3 \times 10^{-2} \text{ m}}{(0.193 \text{ w/MK})} = 0.337$$

$$L = \left(\frac{\text{Volume}}{\text{Area}} \right)_{\text{tube}} = \frac{2050 \text{ cm}^3}{1577 \text{ cm}^2}$$

$$\Rightarrow \frac{Q}{Q_i} = 0.60$$

where Q_i = initial specific heat content of wall

$$Q_i = C_{ps} \rho l \Delta T = (1.26 \text{ J/gK}) (1.2 \text{ g/cm}^3) (1 \text{ cm}) (889 - 298) \\ = 894 \text{ Joules/cm}^3$$

heat absorption is $0.6 Q_i = 536 \text{ Joule/cm}^3$

for tube, 10^5 J is absorbed, $>$ heat evolved. \Rightarrow heat loss to wall is significant.

Since heat loss is linear in ΔT , we may choose an average ΔT over the $1/2 \text{ s}$ transient. At this average a certain heat, Q_w , will be lost to the wall, and a heat, Q_g , will remain with the gas such that

$$Q_r = Q_g + Q_w,$$

where Q_r is the total heat of reaction, $8.2 \times 10^4 \text{ J}$.

From Q_g the actual temperature rise of the gas is calculated, and the actual average pressure is inferred. This average is compared to the initial average used to start the calculation. Using this procedure, it was found that

$$Q_g = 5.0 \times 10^4 \text{ J}$$

$$Q_w = 3.2 \times 10^4 \text{ J}$$

$$T_{avg} = 477 \text{ K}$$

$$T_{max} = 657 \text{ K}$$

The volume ratio due to combustion is

$$V = \frac{\text{Mole } g}{\text{Mole initial}} \frac{T_{avg}}{T_{initial}} = 1 \times \frac{477}{298} = 1.6$$

Thus

$$0.6 V_{\text{tube}} \text{ is likely to be expelled at } T = 477 \text{ K} = 1230 \text{ cm}^3$$

If the temperature is lowered to 310 K (100°F) the volume is reduced to 83 cm^3

The heat loading of gas is

$$Q = MC_p \Delta T = (0.09 \text{ m}) (28.9 \text{ J/M}) (179 \text{ K}) = 465 \text{ J}$$

For heat sink, require sintered material of pore size = $10\ \mu\text{m}$
Only Ni & stainless available,

Ni has higher C_p , λ & $\rho \Rightarrow$ nickel selected

$$\rho = 8914\ \text{Kg/m}^3 = 8.91\ \text{g/cm}^3$$

$$C_p = 430\ \text{J/KgK} = 0.43\ \text{J/gK}$$

if $T_{\text{gas}} = T_{\text{nickel at exit}}$

$$(T_{\text{exit}} - 298\text{K})(M C_p)_{\text{Ni}} = (477\text{K} - T_{\text{exit}})(M C_p)_{\text{exhaust}}$$

Maximum mass of nickel is limited by flow pressure drop developed;

$$\left. \begin{array}{l} \text{Flow rate} = 2\ \text{l/s} \\ \text{Area} = 20\ \text{cm}^2 \end{array} \right\} \text{Velocity} = 100\ \text{cm/s} = 200\ \text{ft/min}$$

$\Delta P = 11.2\ \text{psi/in}$ of porous plate thickness for a volume fraction

$$\frac{\text{Solid Volume}}{\text{Total Volume}} = 0.35$$

$$\rho_{\text{Ni}} = 3.12\ \text{g/cm}^3 \quad 1/8\ \text{in. disk weighs } 20\ \text{g}$$

$$M C_p = 8.6\ \text{J/K} \quad (\text{nickel})$$

$$M C_p = 2.6\ \text{J/K} \quad (\text{gas})$$

$$\Rightarrow T_{\text{exit}} = 339\ \text{K}$$

$$\Rightarrow 1/8\ \text{thick plate lowers temp. from } 477\ \text{K to } 339\ \text{K}$$

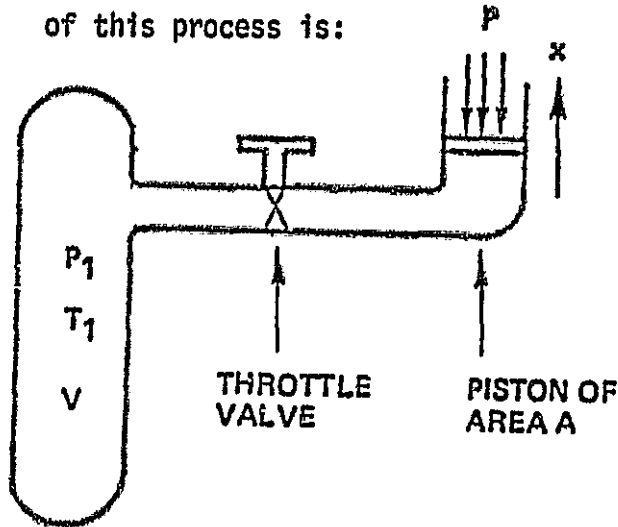
exhaust volume reduced from $1230\ \text{cm}^3$ to $282\ \text{cm}^3$

APPENDIX 2

APPENDIX 2.

"Energy" of stored, compressed air:

The energy stored in compressed air may be thought of as the work which this air could perform if released to the outside environment. The model of this process is:



The work done on the piston is:

$$W_{12} = \int_1^2 P dv \left(= \int_1^2 P A dx \right)$$

but the pressure on the piston is a constant at 1 atm. Thus,

$$W_{12} = P(V_2 - V_1)$$

The problem is thus reduced to determination of the initial and final volume of the gas.

COMPRESSED AIR TANK

The process linking states 1 & 2 is isenthalpic ($dh=0$) as

$$U_2 - U_1 = W_{12} - P(V_2 - V_1)$$

(W_{12} = work done on the system = 0)

$$\underbrace{(U_2 + P_2 V_2)}_{H_2} - \underbrace{(U_1 + P_1 V_1)}_{H_1} = W_{12} = 0$$

At state 1, $P_1 = 10 \text{ atm}$, $V_1 = 800 \text{ ml}$, $T_1 = 298\text{K}$ (77°F)

$P_2 = 1 \text{ atm}$, $V_2 = 8 \text{ L}$, $T_2 = 298\text{K}$

$$W_{12} = 1 \text{ atm} \cdot 7.2 \text{ L} = 7.2 \text{ L atm} = 729 \times 10^3 \text{ L Kg/m s}^2$$

$$(1 \text{ atm} = 101.3 \text{ Kg/m s}^2)$$

$$1 \text{ L} = 1000 \text{ cm}^3 = 10^{-3} \text{ m}^3 = 0.729 \times 10^3 \text{ Kg m}^2/\text{s}^2$$

$$= 0.729 \text{ Joule} \times 10^3$$

$$= 729 \text{ Joule}$$

Single Gas Canister

Need to supply 100 ml/charge x 16 charges = 1.6ℓ at 1 atm

Minimum final pressure = 5 atm

$$p = \frac{NRT}{V}$$

$$N_2 = N_1 - \frac{PV}{RT} = \frac{1.6\ell \times 1 \text{ atm}}{0.082 \times 298} = 0.065 \text{ gmole}$$

$$P_1 = \frac{N_1 P_2}{N_2} = \frac{N_1 P_2}{N_1 - 0.065 \text{ gmole}} = \frac{P_2}{1 - 0.065/N_1} = P_1$$

$$V_1 = \frac{N_1 RT}{P_1} = \frac{N_1 RT}{P_2} (1 - 0.065/N_1) = V_1$$

The energy stored is

$$W_{12} = 1 \text{ atm} (V_2 - V_1) = 1 \text{ atm} \left(\frac{P_1}{P_2} V_1 - V_1 \right)$$

$$= 1 \text{ atm} V_1 (P_1/P_2 - 1) = W_{12}$$

in J: $W_{12} = \left(\frac{P_1}{P_2} - 1 \right) 1.0132 \times 10^2 \times V_1 (\ell)$

N_1/gmole	$P_1(\text{atm})$	$V_1(\ell)$	E (Joule)
1	5.35	4.57	2014
0.5	5.75	2.13	1025
0.2	7.41	0.66	428
0.1	18.29	0.17	229
0.09	18.00	0.12	207
0.08	26.67	0.073	190

Multiple Gas Canisters

1 container per bottle, each must supply 100 ml at 1 atm and begin with a pressure of 5 atm

$$P_1 = 5 \text{ atm}$$

$$P_2 = 1 \text{ atm}$$

$$V_2 = V_1 + 100 \text{ ml}$$

$$P_1 V_1 = P_2 V_2$$

$$V_1 = \frac{P_2 V_2}{P_1} = \frac{P_2 (V_1 + 100 \text{ ml})}{P_1}$$

$$P_1 V_1 = P_2 V_1 + P_2 (100 \text{ ml})$$

$$V_1 (P_1 - P_2) = P_2 (100 \text{ ml})$$

$$V_1 = \frac{P_2 (100 \text{ ml})}{P_1 - P_2}$$

$$P_2 = 1 \text{ atm}$$

$$V_1 = \frac{(1 \text{ atm}) (0.1 \text{ L})}{P_1 - 1 \text{ atm}}$$

$$E = 1 \text{ atm} \times (P_1 V_1 - V_1) \times 1.01325 \times 10^2$$

$$= 101.325 V_1 (P_1 - 1)$$

$$\left| \begin{array}{l} P = \text{atm} \\ V = \text{L} \end{array} \right|$$

$P_1 (\text{atm})$	$V_1 (\text{L})$	$E_1 (\text{J})$	$E(16) (\text{J})$
2	0.100	10.1	162
3	0.050	10.1	162
4	0.033	10.1	162
5	0.025	10.1	162
10	0.011	10.1	162

APPENDIX 3

A 3-1

Particle Motion in an Oscillating Tube

$$\boxed{\text{Drag} = -6\pi r \mu V_{\text{slip}}} \quad = \text{Force} = m\ddot{X}$$

where

$$\boxed{V_{\text{slip}} = \dot{X} - V_{\text{air}}}$$

where

$$V_{\text{air}} = \frac{d}{dt} (A \sin \omega t) = \boxed{A \omega \cos \omega t = V_{\text{air}}}$$

$$\Rightarrow M\ddot{X} = -6\pi r \mu (\dot{X} - A \omega \cos \omega t)$$

$$\ddot{X} + \frac{6\pi r \mu}{m} \dot{X} = \frac{6\pi r \mu}{m} A \omega \cos \omega t$$

$V \equiv \dot{X}$ = absolute motion of particle (in inertial frame)

$$\dot{V} + C_1 V = C_2 \omega \cos \omega t$$

$$(C_1 = \frac{6\pi r \mu}{m} = 6\pi r \mu / 4/3\pi r^3 \rho \quad \& \quad C_2 = A C_1) \quad \boxed{C_1 = \frac{9}{2} \frac{\mu_a}{\rho_p r^2}}$$

Using the integrating factor $e^{C_1 t}$ we have

$$\dot{V} e^{C_1 t} + C_1 V e^{C_1 t} = C_2 \omega e^{C_1 t} \cos \omega t$$

or

$$d(V e^{C_1 t}) = C_2 \omega e^{C_1 t} \cos \omega t dt$$

integrating both sides yields

$$V e^{C_1 t} = C_2 \omega \frac{e^{C_1 t}}{C_1^2 + \omega^2} (C_1 \cos \omega t + \omega \sin \omega t) + C_3$$

$$\text{at } V = 0, t = 0 \text{ so } C_3 = - \frac{C_2 C_1 \omega}{C_1^2 + \omega^2}$$

and the complete solution is

$$\boxed{V = \frac{C_2 \omega}{C_1^2 + \omega^2} (C_1 \cos \omega t + \omega \sin \omega t) - \frac{C_2 C_1 \omega}{C_1^2 + \omega^2} e^{-C_1 t}}$$

Check for a maximum V as you vary ω (not including exp. term as it must $\rightarrow 0$ for large t)

$$c_2 \frac{d}{d\omega} \left[\frac{c_1 \omega}{c_1^2 + \omega^2} \cos \omega t + \frac{\omega^2}{c_1^2 + \omega^2} \sin \omega t \right] =$$

$$c_2 \left[\frac{-(c_1 \omega \cos \omega t)(2\omega) + (c_1^2 + \omega^2)(c_1 \cos \omega t - c_1 \omega^2 \sin \omega t)}{(c_1^2 + \omega^2)^2} \right]$$

$$+ c_2 \left[\frac{(c_1^2 + \omega^2)(2\omega \sin \omega t + \omega^3 \cos \omega t) - 2\omega^3 \sin \omega t}{(c_1^2 + \omega^2)^2} \right]$$

$t_0 = 0 \Rightarrow$

$$-2c_1 \omega^2 \cos \omega t + c_1^3 \cos \omega t + \omega^2 c_1 \cos \omega t$$

$$+ c_1^2 \omega^3 \cos \omega t + \omega^5 \cos \omega t = 0$$

$$\omega^5 + c_1^2 \omega^3 - c_1 \omega^2 + c_1^3 = 0$$

(Matching Cosines)

and

$$-c_1^3 \omega^2 - c_1 \omega^4 + 2c_1^2 \omega + 2\omega^3 - 2\omega^3$$

$$\omega^3 + c_1^2 \omega - 2c_1 = 0$$

(Matching Sines)

Only possible if

$$\omega^5 - c_1 \omega^2 - c_1^4 \omega + 3c_1^3 = 0$$

not likely \Rightarrow no special roots

$$V = A \left[\frac{c_1 \omega}{c_1^2 + \omega^2} (c_1 \cos \omega t + \omega \sin \omega t) - \frac{c_1^2 \omega}{c_1^2 + \omega^2} e^{-c_1 t} \right]$$

for a mechanical shaker

$$0 < \omega < 10^4 \text{ [rad/S]} \text{ and } A \approx 1 \times 10^{-3} \text{ m}$$

(0 to 1600 rpm)

and given $c_1 = \frac{9 \mu_{\text{air}}}{2 (r^2 \rho)_{\text{particle}}}$

$$\mu_{\text{air}} = 1.8 \times 10^{-5} \text{ kg/m-s}$$

$$\rho_{\text{carbon}} = 1.3 \times 10^{-3} \text{ kg/m}^3$$

$$r = 5 \times 10^{-6} \rightarrow 1 \times 10^{-4} \text{ (} 5 \mu\text{m to } 100 \mu\text{m radius} = 10 \text{ to } 200 \mu\text{m diameter)}$$

$$\Rightarrow c_1 = 2500 \text{ for } r = 5 \mu\text{m [1/s]}$$

$$c_1 = 6.2 \text{ for } r = 100 \mu\text{m [1/s]}$$

ORIGINAL PAGE IS
OF POOR QUALITY

The result is an expression for the motion of the particle
→ the slip may be obtained by subtracting the velocity of the air

$$V_{air} = A\omega \cos \omega t$$

$$V_{slip} = V = V_{air} = A \left[\left(\frac{C_1^2 \omega}{C_1^2 + \omega^2} - 1 \right) \cos t + \frac{C_1 \omega^2}{C_1^2 + \omega^2} \sin \omega t - \frac{C_1^2 \omega}{C_1^2 + \omega^2} e^{-C_1 t} \right]$$

The position is found by integration over t

$$X_{slip} = A \left[\left(\frac{-\omega^2}{C_1^2 + \omega^2} \right) \sin \omega t - \frac{C_1 \omega}{C_1^2 + \omega^2} \cos \omega t + \frac{C_1 \omega}{C_1^2 + \omega^2} e^{-C_1 t} \right]$$

The distance of slip over a half cycle (ignoring initial motion which decays exponentially) is (for $\omega t = \pi/4$ to $5\pi/4$)

$$\begin{aligned} A \left[\left(\frac{-\omega^2}{C_1^2 + \omega^2} \right) \frac{2\sqrt{2}}{2} - \frac{C_1 \omega}{C_1^2 + \omega^2} \frac{2\sqrt{2}}{2} \right] &= \frac{2\sqrt{2}}{2} A \frac{C_1^2 - C_1 \omega - C_1^2 - \omega^2}{C_1^2 + \omega^2} \\ &= \frac{2\sqrt{2}}{2} A \frac{\omega^2 + C_1 \omega}{C_1^2 + \omega^2} \end{aligned}$$

NOTE: Better to find where $V = 0$, integrate distance between those 2 points.

$$V = A\omega \left[\left(\frac{C_1^2}{C_1^2 + \omega^2} - 1 \right) \cos \omega t + \frac{C_1 \omega}{C_1^2 + \omega^2} \sin \omega t \right]$$

$$V = 0 @ \frac{-\omega^2}{C_1^2 + \omega^2} \cos \omega t + \frac{C_1 \omega \sin \omega t}{C_1^2 + \omega^2} = 0$$

$$\frac{C_1 \omega}{C_1^2 + \omega^2} \sin \omega t = \frac{\omega^2}{C_1^2 + \omega^2} \cos \omega t$$

$$\sin \omega t = \frac{\omega}{C_1} \cos \omega t$$

$$\tan \omega t = \frac{\omega}{C_1}$$

$$\Rightarrow \text{for } C_1 \gg \omega \text{ (low freq. small particles) look at } 0 \text{ to } \pi \rightarrow \Delta X = 2A \frac{C_1 \omega}{C_1^2 + \omega^2}$$

for $C_1 \approx \omega$ (intermediate) look at $\pi/4$ to $5\pi/4 \rightarrow \Delta X = \frac{2A}{\sqrt{2}} \frac{\omega^2 + C_1 \omega}{C_1^2 + \omega^2}$

for $C_1 \ll \omega$ (high freq. large particles) look at

$$\left. \pi/2 \text{ to } 3\pi/2 \Delta X = \frac{2A \omega^2}{C_1^2 + \omega^2} \right]$$

Mechanisms at Particle Collision

- 1) Particles may collide with the wall since they have slip and the walls (by definition) have 0 slip.
- 2) Particle slip depends on particle diameter (through C_1) \rightarrow particles of differing diameter have different velocity and may collide.
- 3) The air may not track wall motion exactly, hence a flow field may be superimposed on the assumed (oscillatory) velocity field.

Quantify These Effects:

- 1) 2 issues:
 - a) What is the slip distance for a given wall amplitude; \rightarrow how many particles are enclosed in the shell around the walls of this thickness?
 - b) A particle in contact with the wall will be ejected as the wall moves inward and then retracts. How far will the particle travel into the gas? How does this compare with the mean free path?
- 2) Assume 2 particle sizes (e.g. $\pm 1 \sigma$). What is the difference in their slip distances? How does this compare to the mean free path?
- 3) Analyze likely flow field for vibrating closed pipe.

Experimental Model: Since no particles have $\rho = \rho_{\text{air}}$, fill tube with H_2O and polystyrene ($g_s = 1.05$) and shake. Try to match Reynolds # or slip distance.

All of the collisions are a function of mean free path (except wall collisions).

⇒ Calculate Mean Free Path

$$\ell = \frac{1}{\sqrt{2} n \pi r^2} \quad (\ell = \text{mfp}, n = \text{\#density})$$

$$n = \frac{\text{\# particles}}{\text{tube volume}}$$

$$\text{\# particles} = \text{mass of fuel} / \rho \pi r^3 \quad 4/3 \quad (\rho \text{ \& } r \text{ of particle})$$

$$= (\text{mass of air}) \cdot (\text{Fuel/air ratio}) / 4/3 \rho \pi r^3$$

$$\text{mass of air} = \text{tube volume} \times \rho_{\text{air}}$$

$$\Rightarrow n = \frac{(\text{tube volume}) (\rho_{\text{air}}) (\text{fuel/air ratio}) (1/4/3 \rho_p \pi r^3)}{\text{Tube volume}}$$

$$\frac{\rho_{\text{air}} f/a}{\rho_p 4 \pi r^3} = n$$

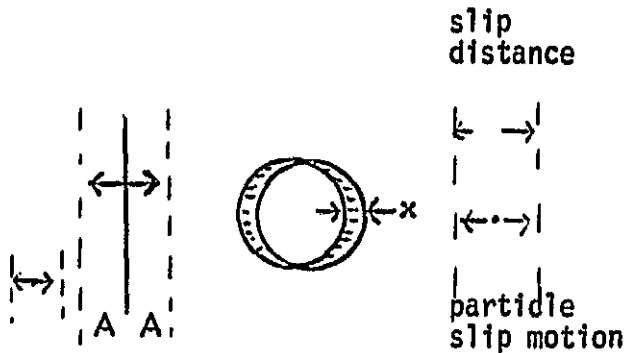
where r = particle radius
 f/a = fuel mass/air mass

$$\Rightarrow \ell = \frac{\rho_p 4 \pi r^3}{3 \rho_a (f/a) \sqrt{2} \pi r^2} = \frac{2 \sqrt{2} \rho_p r}{3 \rho_a (f/a)} = \ell$$

ORIGINAL PAGE IS
OF POOR QUALITY

Fraction of Particles Colliding with the Wall:

$$f = \frac{\text{Interaction Volume}}{\text{Tube Volume}} = \frac{(\text{Slip distance}) \times \text{Tube Wall Surface}}{\text{Tube Volume}}$$



$$= \frac{4 r x_0 \cdot L}{\pi r^2 L}$$

$$= \frac{2 x_0}{D} = f$$

Since a particle must slip towards the wall, only 1/2 of slip contributes to particle/wall collisions.

Wall Motion

if slip, $x = 0$, no collisions \Rightarrow width of wall collision Zone = $1/2X$

\Rightarrow (1) is modified

$$f = \frac{2 X}{D}$$

$$\text{where } X = \frac{\omega A}{C_1^2 + \omega^2} \left[\omega \sin \omega t + C_1 \cos \omega t \right] \begin{matrix} B = \omega t \\ B + \pi = \omega t \end{matrix}$$

and B is chosen to secure a maximum of the bracketed quantity.

$$\Rightarrow B = \text{Arctan } \omega/C_1$$

(e.g. for $\omega \ll C_1$, $B = 0$, for $\omega \gg C_1$, $B = \pi/2$)

Typical Values:

$$D = 0.05 \text{ m}$$

$$A = 0.001 \text{ m}$$

$$\omega = 628 \text{ s}^{-1} (100 \text{ rps}) \text{ or}$$

$$W = 6280 \text{ s}^{-1} (1000 \text{ rps})$$

$$C_1 = 2500 \text{ s}^{-1} (r = 5 \mu\text{m}) \text{ or}$$

$$C_1 = 6.2 \text{ s}^{-1} (r = 100 \mu\text{m})$$

$$(B = 14.1^\circ)$$

$$(B = 89.4^\circ)$$

ORIGINAL PAGE IS
OF POOR QUALITY

$\omega = 628$ $r = 5 \mu m \rightarrow f = 0.6\%$	$\omega = 6289$ $r = 1 \mu m \rightarrow f = 2.4\%$
$\omega = 628$ $r = 100 \mu m \rightarrow f = 2.6\%$	$\omega = 6280$ $r = 100 \mu m \rightarrow f = 7.1\%$

*Want area of



Since slip is in x direction only
i.e. should be $\frac{1}{x_0} \int x_0 \cos \theta$ which
adds factor.

$$\text{Area} = 2\pi r x_0 \left(\frac{\int_{-\pi/2}^{\pi/2} \sin \theta d\theta}{\int_{-\pi/2}^{\pi/2} d\theta} \right) = 2\pi r x_0 \left(\frac{2 x_0}{\pi x_0} \right) = 4 r x_0$$

Calculation of max. penetration of particle launched from tube wall by vibration.

$$\text{Drag} = -6\pi r \mu V_{\text{slip}}$$

Assume particle launched by wall and wall does not recoil. This is conservative: recoiling wall will slow particle, but since next forward wall pulse will propel it further, this is not an overly conservative assumption.

$\Rightarrow V_{\text{slip}} = V_{\text{particle}}$: initial velocity is $A\omega$
(A is vibration amplitude, ω is frequency)

$$M\ddot{X} = \text{Drag} \Rightarrow \ddot{X} = \frac{6\pi r \mu}{\text{Mass}} \dot{X} = -C_1 \dot{X}$$

$$\ddot{X} + C_1 \dot{X} = 0$$

$$\dot{V} + C_1 V = 0$$

which has solution:

$$V = A_1 e^{-C_1 t}$$

$$\text{at } T = 0 \quad V = A\omega \Rightarrow A_1 = A\omega$$

$$V = A\omega e^{-C_1 t}$$

$$X = \text{penetration length} = \int_0^{\infty} V dt = \int_0^{\infty} A\omega e^{-C_1 t} dt$$

$$X = A\omega / C_1$$

ORIGINAL PAGE 10
OF POOR QUALITY

Typically, the product $A\omega$ will be less than 1 m/s because acceleration $= A\omega^2 \Rightarrow$ for amplitude 2mm (2×10^{-3} m). ω must be $500.s^{-1} \approx 80$ Hz yielding an acceleration of 500 g which will be mechanically difficult to sustain.

For 10 μ m diameter particle $C_1 = 2500s^{-1}$

$$\Rightarrow x = \frac{1 \text{ m/s}}{2500/s} = 0.4 \text{ mm} = 400 \mu\text{m}$$

for more realistic designs, this number may be less than 100 μ m. For stoichiometric combustion of 10 μ m particles, ℓ , the mean free path \approx 61 mm so the average launched particle would suffer

$$\frac{0.4}{61} = 0.007 \text{ collisions.}$$

Add some typical numbers:

Tube length = 80 cm

Tube diameter = 5 cm

Tube volume $= \pi r^2 h = 1570 \text{ cm}^3 = 1.57 \times 10^3 \text{ cm}^3 = 1.57 \times 10^{-3} \text{ M}^3$

$\rho_{\text{air}} = 1.2 \text{ kg/m}^3$

\Rightarrow Tube has $1.88 \times 10^{-3} \text{ kg air}$

Air is 20% O_2 (by volume) \Rightarrow

$M_{\text{air}} = 0.2 \times 32 + 0.8 \times 28 = 6.4 + 22.4 = 28.8 \text{ kg/mole}$

Oxygen = $\frac{0.2 \times 32}{0.2 \times 32 + 0.8 \times 28} = 0.22\%$ of air by mass

\Rightarrow Tube has $4.2 \times 10^{-4} \text{ kg } O_2$

Coal Combustion:

$C + O_2 \rightarrow CO_2 \Rightarrow 12\text{g coal req. / } 32 \text{ g } O_2$

$\Rightarrow 1.575 \times 10^{-4} \text{ kg of coal}$

Density of coal $= 1.3 \text{ g/cm}^3 = 1.3 \times 10^{-3} \text{ kg/M}^3$

\Rightarrow need $1.21 \times 10^{-7} \text{ M}^3 \text{ coal}$

ORIGINAL PAGE IS
OF POOR QUALITY

Assume 10 μm particles: $V/\text{particle} = 5.24 \times 10^{-16}$ meter

$$\Rightarrow 2.3 \times 10^{-8} \text{ particles in } 1.57 \times 10^{-3} \text{ m}^3$$

$$= 1.47 \times 10^{11} \text{ particles/m}^3$$

$$\ell = \frac{1}{\sqrt{2} n \pi r^2} = 0.0613 \text{ m} = \text{Mean free path}$$

$$d = \frac{\omega c_2}{c_1} \frac{1}{\omega^2 + c_1^2} \quad \text{in appropriate units}$$



Calculation of Acceleration as Functional Amplitude & Frequency:

$$x = A \sin \omega t \quad \dot{x} = A \omega \cos \omega t \Rightarrow \dot{x}(\text{max}) = A \omega$$

$$\ddot{x} = A \omega^2 \sin \omega t \Rightarrow \ddot{x}(\text{max}) = A \omega^2$$

ω in rad/sec = /sec

A in mm

$$1g = 9800 \text{ mm/sec}^2$$

Assume A = 2 mm (for rubber bumpers)

$$\omega = 70 \text{ rad/sec (1g)}$$

$$= 11 \text{ rpm for 1g} \rightarrow V = 140 \text{ mm/sec}$$

$$= 35 \text{ rpm for 10g} \rightarrow V = 445 \text{ mm/sec}$$

ORIGINAL PAGE 10
OF POOR QUALITY

Comparison may be made between the distance a particle may be thrown from the wall and the mean free path within the particle cloud. Particle of diameter ± 1 standard deviation from the mean will slip different amounts. This difference may be compared to the mean free path to find the fraction of particles likely to collide per tube oscillation.

The mean free path, ℓ , of particles with radius r is

$$\ell = \frac{1}{\sqrt{2} n \pi r^2} \quad (4)$$

here n , particle number density, is

$$n = \frac{3 \rho_a f}{4 \pi \rho_p r^3} \quad (5)$$

Here f is the fuel/air mass ratio ρ is the density of air (subscript a) and fuel (subscript p). Thus

$$\ell = \frac{2 \sqrt{2} \rho_p r}{3 \rho_a f} \quad (6)$$

The drag, D , is assumed to follow Stokes' law thus

$$D = -6 \pi r \mu V_s \quad (7)$$

Where μ is the air viscosity and V_s the ship velocity. Assuming the air velocity V_a , is the same as the tube wall, we have

$$V_a = A \omega \cos \omega t \quad (8)$$

for a wall oscillating with amplitude A and frequency ω .

Solving for the particle velocity, V_p , given by

$$V_p = V_a + V_s \quad (9)$$

is

$$V_p = \frac{C_2 \omega}{C_1^2 + \omega^2} (C_1 \cos \omega t + \omega \sin \omega t) - \frac{C_2 C_1 \omega}{C_1^2 + \omega^2} - C_1 t \quad (10)$$

where

$$C_1 = \frac{6 \pi r \mu}{4/3 \pi r^3 \rho_p}$$

and

$$C_2 = A C_1$$

No special roots occur for V_p by varying ω , C_1 and C_2 so it is not likely to contain resonance or other singularities where V would be dramatically changed. To conceptualize the motion, the following values are assumed for the particular configuration

$$0 \leq \omega \leq 10^4 \text{ [rad/s]}$$

$$A \approx 10^{-3} \text{ m}$$

$$\mu = 1.8 \times 10^5 \text{ kg/m}\cdot\text{s}$$

$$\rho = 1.3 \times 10^3 \text{ kg/m}^3$$

$$5 \times 10^{-6} \text{ m} \leq r \leq 1 \times 10^{-4} \text{ m}$$

thus

$$C_1 = 2500 \text{ s}^{-1} \text{ for } r = 5 \mu\text{m}$$

$$C_1 = 6.2 \text{ s}^{-1} \text{ for } r = 100 \mu\text{m}$$

The slip velocity is found from equations 8, 9 and 10;

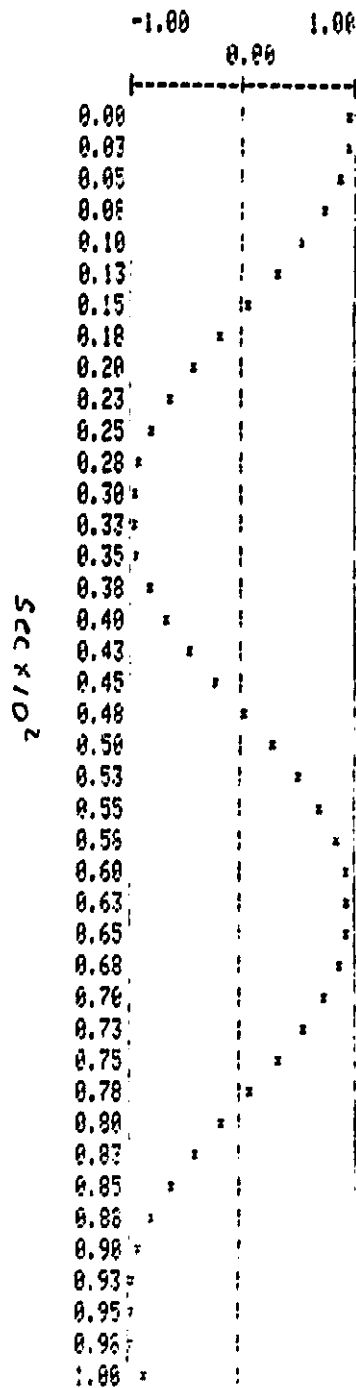
$$V_s = A \left[\left(\frac{c_1^2 \omega}{c_1^2 + \omega^2} - \omega \right) \cos \omega t + \frac{c_1 \omega^2}{c_1^2 + \omega^2} \sin \omega t - \frac{c_1^2 \omega}{c_1^2 + \omega^2} e^{-c_1 t} \right] \quad (11)$$

— Figure III 1 shows the slip velocity (a) and the tube velocity (b) for a 200 μm diameter coal particle being forced at 10 rad/sec with amplitude normalized to 1. The amplitude scales are identical on the two charts. The phase shift indicates that the particle is almost stationary in the moving air. The maximum slip occurs at the velocity extreme and is about 10% of the maximum. Mixing under these conditions would be slight. Figure III 2(a) shows a similar plot for a very small (10 μm diameter) particle under the same conditions. After an extremely short starting transient (2 ms) the particle slip velocity is zero. It will track the air and suffer virtually no wall collision. Excited at 100 rad/sec the same smaller particle (Fig. III 2b) maintains a slip velocity at a phase angle of about 90° with a maximum velocity about 20% of the wall velocity. Mixing of particles is best done at a frequency, ω , allowing the particle neither to simply remain at rest (ω too high) nor to track the air motion precisely (ω too low).

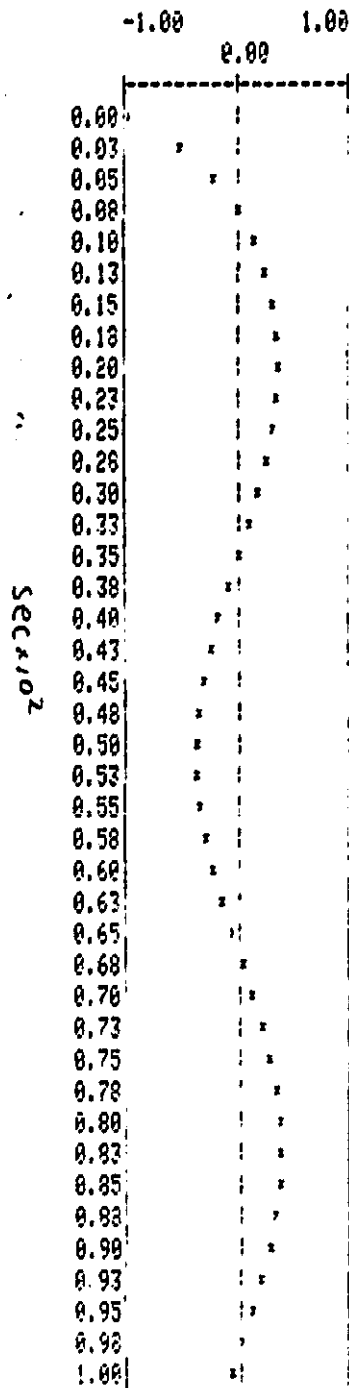
To find the distance the particle slips compared to the wall motion over any half-cycle, equation 11 is integrated between times when $V_s = 0$.

Note that this is not the same as integrating over $0 < \omega t < \pi$ as the particle continues to move in a direction for a short time after the

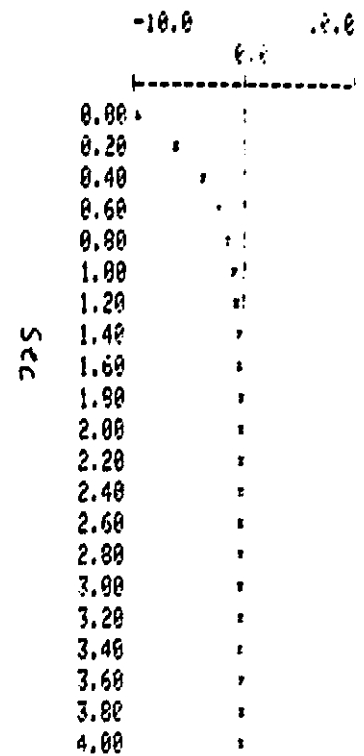
Figure III.3 shows the computer program used to generate the dynamics plots.



(c)



(b)



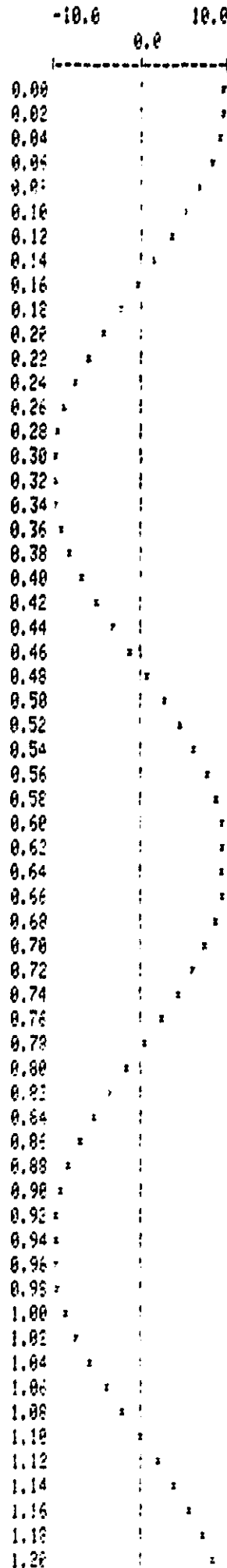
(a)

Figure III.1
Slip velocity for a 10 μ m
diameter coal particle at
10 rad/sec (a) and 1000 rad/sec
(b), compared with the wall
velocity at 1000 rad/sec (c).

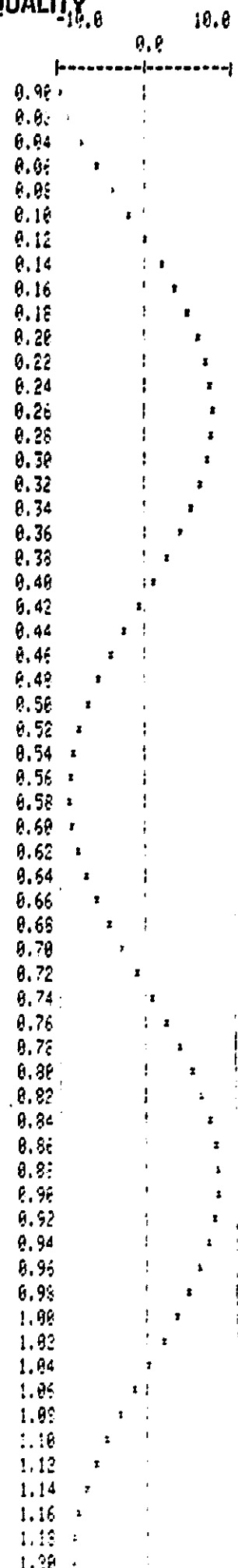
Figure III.2
Comparison of slip
velocity, V_s (a) with
tube wall velocity,
 V_a (b). 200 μ m diameter
coal particle, amplitude = 1,
 $\omega = 10$ rad/sec. Horizontal
axis is in seconds.

ORIGINAL PAGE IS
OF POOR QUALITY

(b)



(a)



ORIGINAL PAGE IS
OF POOR QUALITY .

ORIGINAL PAGE IS

XEC *P*
PRP *P*

Figure III.3

Program for calculation of
particle dynamic response in
oscillating medium.

01 LBL *P*
02 STO 31
→ 03 RCL 20
04 *
05 STO 30
06 COS
07 RCL 21
08 X+2
09 RCL 20
10 *
11 RCL 21
12 X+2
13 RCL 20
14 X+2
15 +
16 /
17 RCL 20
18 -
19 *
20 RCL 20
21 X+2
22 RCL 21
23 *
24 RCL 21
25 X+2
26 RCL 20
27 X+2
28 +
29 /
30 RCL 30
31 SIN
32 *
33 +
34 RCL 21
35 COS
36 RCL 31
37 *
38 E+Y
39 RCL 21
40 X+2
41 *
42 RCL 20
43 COS
44 *
45 RCL 21
46 X+2
47 RCL 20
48 X+2
49 +
50
51 +
52 END

APPENDIX 4

The acoustic driver will be cemented on center to the end plate (Fig 4.5) using silicon-rubber cement.

Parts list for acoustic mixer (in addition to those specified for the prop-driven mixer).

- End plate (Fig. 4.5)
- JBL Professional Series Model 2425 H/J Compression Driver (\$250.00)
- 2 x Wavetek Model 190 Function Generators \$895.00 each. (\$1790.00)
- McIntosh Model 502 Compact Power Amplifier (\$735.00)

Acoustic Resonance for 81 cm Tube occurs at

$$f_m = \frac{344 \text{ m/s}}{2 \times 0.81} \quad m = 212.35 \text{ m}^{-1}$$

the number of nodes of zero particle velocity is given by

$$1 + m$$

NOTE: 2 of these nodes are at the ends. Excitation strategy should be to alternatively excite modes of oscillation with widely separated nodes to promote particle motion. Also, enough nodes should be present to keep the number of particles in tube-end nodes relatively small. Also the response of the driver is limited below 800 Hz.

To calculate the particle velocity (average) use

$$v_m(x) = \frac{p_m(x=0)}{\rho c} \left[\frac{\omega_m}{U} \right] \sin \frac{M\pi x}{L}$$

where

$$p_m(x=0) = \frac{c^2 Q_0 \rho \omega}{V [4\omega_m^2 K_m^2 + (\omega^2 - \omega_m^2)^2]^{1/2}}$$

(Beranek, "Noise and Vibration Control" McGraw Hill 1971)

thus on average, at $\omega = \omega_m$

$$\bar{U}_m = \frac{c Q_0}{2 V K_m \sqrt{2}}$$

Beranek points out that

$$K_m \approx 20\pi m$$

for rigid tubes

$$C = 344 \text{ m/s}$$

$$V = \pi r^2 L = \pi (2.8 \times 10^{-2})^2 0.81 = 2 \times 10^{-3} \text{ m}^3$$

$$Q_0 = \text{Acoustic element area} \times \text{displacement} \times \text{frequency}$$

$$= \pi (12.5 \times 10^{-3} \text{ m})^2 \times 10^{-4} \text{ m} \times 212.35 \text{ m}$$

$$= 1 \times 10^{-5} \text{ m} \quad (\text{note this assumes diaphragm displacement constant at } 0.1 \text{ mm over a range of frequencies})$$

$$\Rightarrow \bar{U}_m = 1.4 \text{ cm/s}$$

One mixing strategy is to pick a resonant frequency,

$$f_1 = f \cdot m_1$$

After allowing sufficient time for particles to group at the zero velocity points, switch to the next resonant frequency,

$$f_2 = f \cdot m_2$$

where

$$m_2 = 1 + m_1$$

Sufficient time should be allowed at this second resonant frequency to allow particles to move to the new zero-velocity points. The frequency is then reset to f_1 and the process repeated.

The distance between nodes, X , is

$$X_1 = \frac{L}{2m_1}$$

where L is the tube length. It can be seen that the distance from a node at $M = M_1$ to a node at $M = M_1 + 1$, X_1 is

$$X_1 = \frac{L}{M_1(M_1+1)}$$

Using the average particle velocity of 1.4 cm/s, Figure IV.1 has been constructed as a guide for operation of the acoustic resonator. Upon establishment of a resonant frequency, f_1 , the governing oscillator should drive the acoustic driver oscillator (ADO) with a square wave signal causing the ADO to switch between f_1 and $f_1 + 1$ at a frequency no greater than that

found on the ordinate of Figure IV.1 corresponding to the frequency f_i found on the axis.

- 1) Find a resonance at frequency $f_i = f_1 m_i$ (sine wave setting)
- 2) Find the next resonance at $f_{i+1} = f_1 (M_i + 1)$
- 3) Use Figure 22 to find f'_{\max} corresponding to f_i
- 4) Set the governing oscillator (GO) to square wave at a frequency less than or equal to f'_{\max} .
- 5) Set the ADO so that the GO signal causes it to switch between f_i and f_{i+1}
- 6) Apply this signal to the test apparatus, adjusting the GO frequency as necessary to attain good mixing.

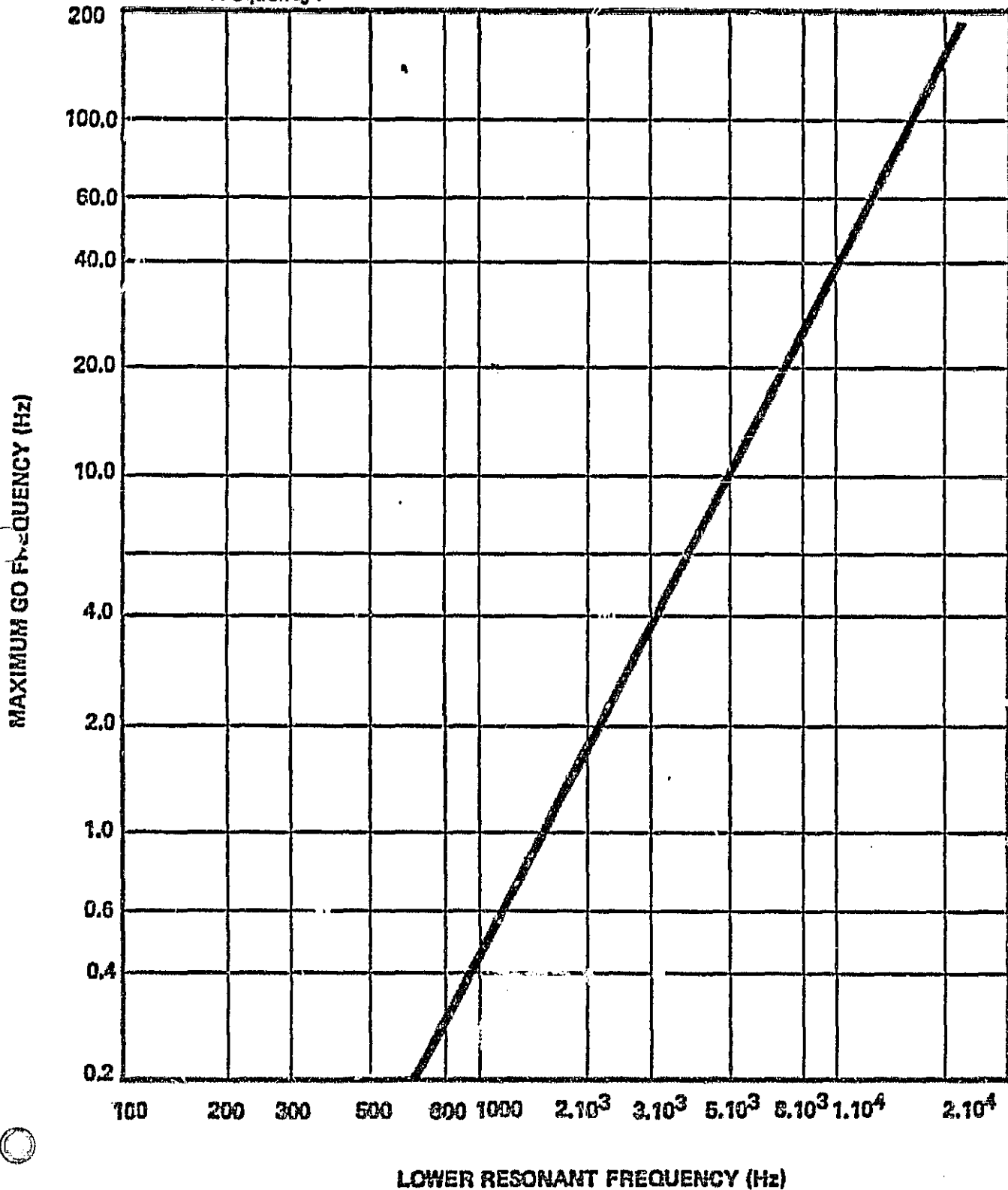
NOTE:

- 1) The switching (GO) frequency is approximate and should be adjusted for best results.
- 2) This is one of many possible mixing schemes. Others should be investigated.
- 3) If particles tend to collect at tube ends, set the GO so that the ADO is not always at a resonant frequency. One technique may be to operate the GO with a Trapezoidal or Triangular waveform instead of square wave.

Fig. IV.1

ORIGINAL PAGE IS
OF POOR QUALITY

Maximum governing oscillator switching frequency as a
function of lower resonance acoustic driver oscillator
frequency.



APPENDIX 5

Acoustic Loss Calculation:

- Assume a sound amplitude (db) which would exist in the tube with only dissipation being viscous.
- Calculate pressure amplitude for this case.
- Calculate boundary layer losses for this amplitude.
- Assume losses via impedance mismatch and leakage will be 10 x above losses.
- Calculate new pressure amplitude and new energy.

1) Assume $\frac{140 \text{ db}}{P}$

2) $\text{db} = 20 \log \frac{P}{2 \times 10^{-5}} \Rightarrow P = 200 \text{ n/m}^2$

3) $\langle \mathcal{E} \rangle = \left(\frac{A^2}{4 \rho_0 a_0^2} \right) (\pi R^2 L)$

$A = 200 \text{ n/m}^2$

$R = 2.6 \text{ cm} = 0.026 \text{ m}$

$\rho_0 = 1.29 \text{ kg/m}^3$

$L = 80 \text{ cm} = 0.8 \text{ m}$

$a_0 = 343 \text{ m/s}$

$\langle \mathcal{E} \rangle = 1.12 \times 10^{-4}$

$\alpha = - \frac{2}{D} \sqrt{\frac{\omega \nu^3}{2}} \left[1 + \frac{\gamma - 1}{\sqrt{Pr}} \right]$

$Pr = 0.72$

$D = 0.052 \text{ m}$

$\omega = 6280 \text{ (} 2 \pi \times 1000 \text{ Hz)}$

$\nu = 1.57 \times 10^{-5} \text{ M}^2/\text{s}$

$\gamma = 1.4$

$\alpha = -12.6 \text{ (s}^{-1}\text{)}$

4) $\alpha' = -126 \text{ (s}^{-1}\text{)}$

ORIGINAL PAGE IS
OF POOR QUALITY

$$5) \langle \dot{\mathcal{E}} \rangle = 2 \alpha \langle \mathcal{E} \rangle = 2.8 \times 10^{-3} \quad (\text{in no-loss case})$$

$$\Rightarrow \langle \dot{\mathcal{E}}' \rangle = 1.12 \times 10^{-5} \quad (\text{so that } \langle \dot{\mathcal{E}}' \rangle = \langle \dot{\mathcal{E}} \rangle)$$

$$P \propto \sqrt{\langle \mathcal{E} \rangle} \quad \frac{P'}{P} \propto \frac{\sqrt{\langle \mathcal{E}' \rangle}}{\sqrt{\langle \mathcal{E} \rangle}} = \sqrt{10} = 3.2$$

$$\Rightarrow P' = \frac{P}{3.2}$$

$$\Delta \text{db} = 20 \log_{10} 3.2 = 10 \text{db}$$

6) Conclusion: Pressure is factor of 3 \rightarrow 67% loss in particle drive force
db loss is 10 db

\Rightarrow need 10 x power to make-up.

Power loss to diaphragm: (aluminum sheet, 0.1mm thick) (4 mil)

- Calculate energy balance

1) of speaker

2) of diaphragm motion

$$\text{Speaker energy} = 1.12 \times 10^{-4} \text{ J} \Rightarrow$$

$$E = \frac{1}{2} \rho_a u^2 \Rightarrow u = (2 E / \rho_a)^{\frac{1}{2}} = 1.32 \times 10^{-2} \text{ m/s}$$

for diaphragm:

$$E = \frac{1}{2} m v^2$$

$$m = \rho_a t = 2.7 \times 10^3 \text{ kg/m}^3 \cdot 2.12 \times 10^{-3} \text{ m}^2 \cdot 1 \times 10^{-4} \text{ m}$$

$$= 5.8 \times 10^{-4} \text{ kg}$$

$$\Rightarrow V = (2E/m)^{\frac{1}{2}} = 0.62 \text{ m/s} = 6.2 \times 10^{-1} \text{ m/s}$$

$$\text{Actual } V = 1.32 \times 10^{-2} \quad E = \frac{1}{2} m v^2 = 2.02 \times 10^{-7} \text{ J}$$

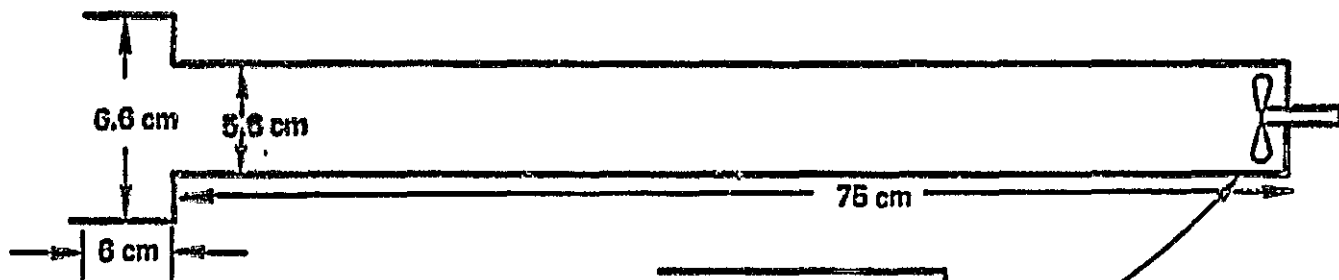
= 0.5% coupling efficiency (27 db loss)

$$\frac{(p_a)_{al}}{(p_a)_{air}} = 6 \times 10^3 \Rightarrow \text{Via impedance mismatch}$$

expect 38 db loss across
diaphragm.

APPENDIX 6

Design of Tube with Propeller



Clearance?
Pitch?
RPM?
Diameter?
Offset?

Feed through method?
Drive method?
 C_L or offset?

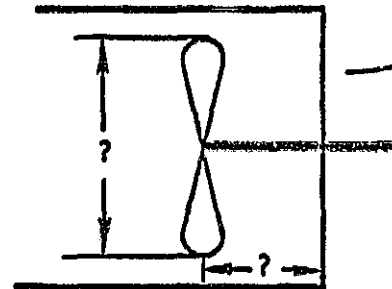


Fig. VI.1a

Prop Design: Need jet of sufficient momentum to reach end of tube
(want recirculation over entire length).

For jets into stagnant fluid (i.e. coflowing stream of zero velocity) the initial jet velocity remains above 10% of its initial velocity at least 80 jet diameters downstream (see e.g. Field, M.A. et al "Combustion of Pulverised Coal" Fig. 2.19). This is not a function of initial jet momentum. Neither is the observation that spreading half angles are ~ 5 to 6° . At this angle, a jet fills a tube 11 to 12 diameters downstream.

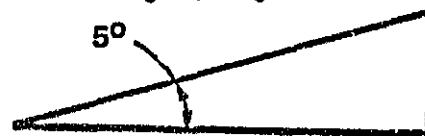


Fig. VI.1b

11.4

Propeller diameter is thus sized so that

- 1) diameter not so large as to force narrow recirculation zone (high shear)
- 2) diameter not so small as to force narrow, high velocity initial jet (also high shear)

ORIGINAL PAGE IS
OF POOR QUALITY

No reliable expression for interjet shear force (or wall shear force) is available, tradeoff is arbitrary. Assuming return flow must be lower velocity than initial jet, use following dimensions

Propeller Diameter = 2.5 cm (swept area = 4.9 cm^2)

Tube Inside Diameter = 5.6 cm (total area = 24.6 cm^2)

Unswept area = 19.7 cm^2

⇒ return airspeed = jet speed $\cdot \frac{4.9 \text{ cm}^2}{19.7 \text{ cm}^2} = 25\% \text{ of jet speed.}$

Likely shaft diameter: 1/8th inch 3.2 mm

Full Scale End View:

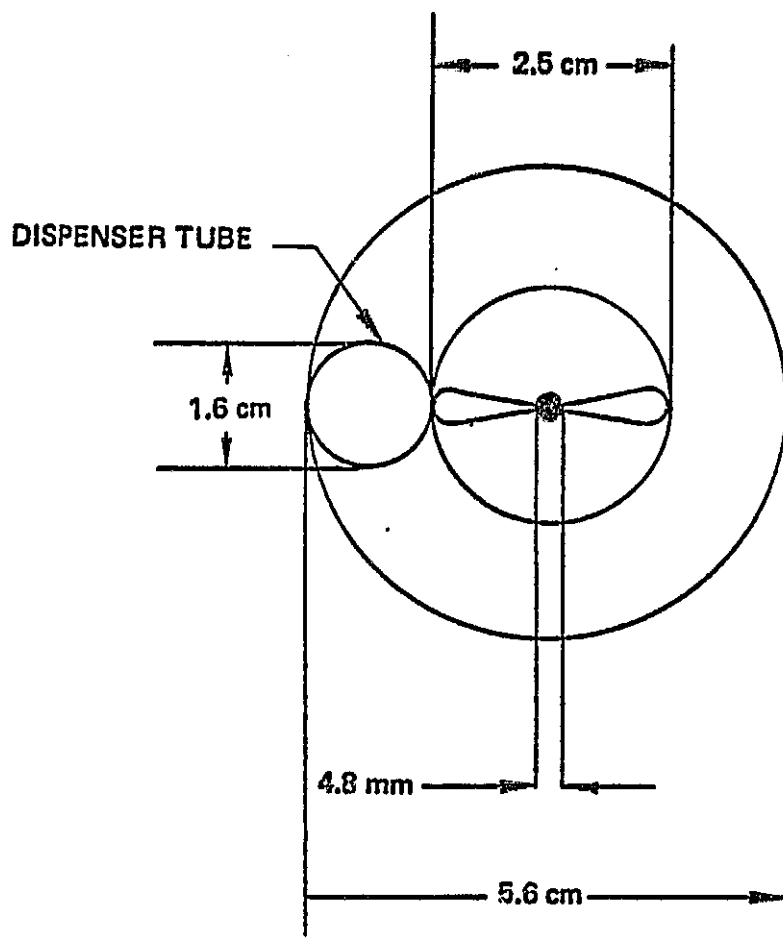


Figure VI.2

Clearance MUST be greater
than $5.6 - 2.5/2 = 1.6 \text{ cm}$
+ allowance for flow turning
= 2.0 cm

ORIGINAL PAGE IS
OF POOR QUALITY

Clearance should be sized so that the return flow does not see an area restriction

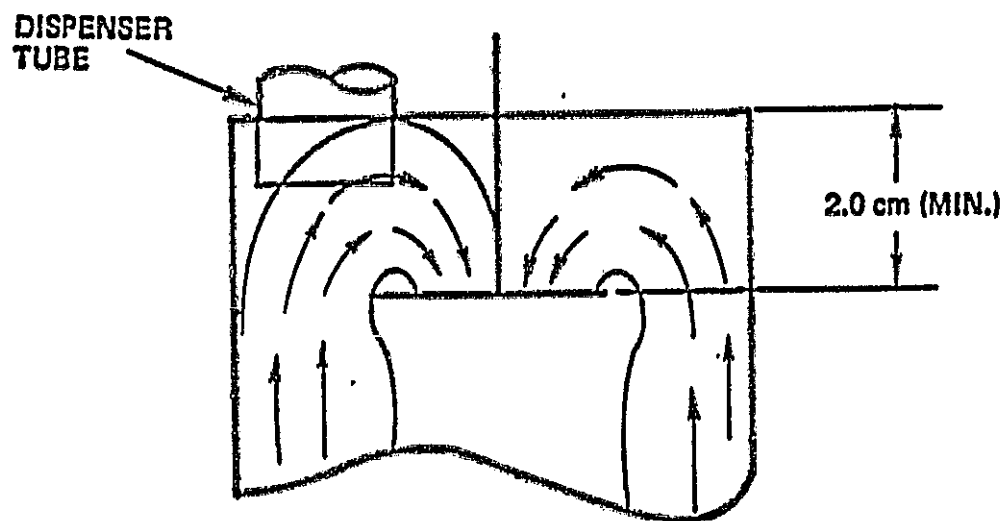


Figure VI.3

APPENDIX 7

Notes on Particle Size Scaling

Both the acoustic and propeller mixers are expected to suffer performance degradation at 1g compared to shuttle conditions (10^{-3} to 10^{-4} g). Thus acceptable operation in laboratory tests supports strongly their successful operation at orbit. This is mainly because any mixer must be able to compensate for particle settling. Settling occurs at the terminal particle velocity, V_t , given by

$$V_t = g r^2 \frac{2\rho}{9\mu} \quad (\text{stokes}) \quad \langle 1 \rangle$$

where g is the gravitational acceleration (local), r the particle radius, ρ the particle density and μ the gas (air) viscosity through which the particle falls. We see that if g is reduced by 10^{-3} to 10^{-4} , the settling velocity and hence the difficulty of sustaining homogenous mixing is reduced proportionately.

Should one desire to scale the experiment to orbital conditions during ground testing, eq. $\langle 1 \rangle$ shows that the particle radius for the ground test needs to be adjusted. This adjustment should be calculated by

$$r' = r \sqrt{g} \quad \langle 2 \rangle$$

Where r' is the scaled particle radius for the ground experiment. r is the particle size of the space experiment we wish to model, and g is the fraction of earth gravity anticipated in orbit. For example, to model the behavior of $200 \mu\text{m}$ radius particles at 10^{-3} g on the shuttle, the ground test should use

$$r' = 200 \mu\text{m} \sqrt{10^{-3}},$$

$$r' = 6.3 \mu\text{m} \text{ radius particles.}$$

Further Notes on Particle Size Scaling

ORIGINAL PAGE IS
OF POOR QUALITY

The argument of the preceeding page is valid for flows of Reynolds number < 1 ,

$$Re = \frac{L U \rho_f}{\mu_f}$$

here U is given by eg. <1> so that

$$Re = \frac{L \rho_f}{\mu_f} g r^2 \frac{2 \rho_s}{9 \mu_f} = \frac{4 \rho_f g r^3 \rho_s}{9 \mu_f^2}$$

for $Re \leq 1$ we have

$$r^3 \leq \frac{9 \mu_f^2}{4 \rho_f g \rho_s}$$

$$(air) \left\{ \begin{array}{l} \mu_f = 1.85 \times 10^{-5} \text{ kg/(m)(s)} \\ \rho_f = 1.205 \text{ kg/m}^3 \\ g = 9.8 \text{ m/s} \end{array} \right.$$

$$\text{for Pocahantas coal} \\ \rho_s = 1346 \text{ kg/m}^3$$

$$\Rightarrow r \leq 3.65 \times 10^{-5} \text{ m} \quad D \leq 73 \mu\text{m}$$

checking this calculation, at $r = 3.65 \times 10^{-5} \text{ m}$

$$V = 0.21 \text{ m/s}$$

and

$$Rc = 1.00$$

For particles of larger diameter, we may maintain the assumption of spherical shape. The drag law, however, changes from

$$C_d = \frac{D}{\frac{1}{2} \rho U^2 \pi a^2} = \frac{24}{R}$$

to

$$C_d \approx \frac{24}{R^{2/3}}$$

<3>

ORIGINAL PAGE IS
OF POOR QUALITY

Thus equating body and drag forces

$$\rho_s \frac{4}{3} \pi r^3 g = \frac{12 \rho_f v^2 \pi r^2}{R^{2/3}}$$

Solving for the velocity yields

$$v_t = \left[\frac{\rho_s^3 g^3 r^5}{182.2 \rho_f \mu_f^2} \right]^{1/4} \quad (\text{modified Oseen})$$

Thus for particles larger than $D = 73 \mu\text{m}$, the settling velocity is proportional to

$$v_t \propto g^{3/4} r^{5/4}$$

so that equation <2> becomes

$$r' = r g^{3/5}$$

The results of the particle scaling law are plotted for $g = 10^{-2}$, 10^{-3} and $10^{-4} g$ in Figure VII.1

As a check, for the largest particle considered, 2000 μm diameter

$$v_t = 13.2 \text{ m/s}$$

$$R_c = 1720$$

The experimental drag coefficient here is 0.4, while the correlation of eq <3> predicts 0.17. Thus for $R_c > 460$, we let $C_d = 0.4$. Now the equation of body and drag forces is

$$\rho_s \frac{4}{3} \pi r^3 g = \frac{1}{5} \rho_f v^2 \pi r^2$$

so that the terminal velocity is given by

$$v_t = 2 \sqrt{\frac{5 \rho_s r g}{3 \rho_f}}$$

and the Reynolds number is given by

$$R_c = \frac{2rV_t\rho_f}{\mu_f} = \frac{4r\sqrt{5\rho_a\rho_tgr}}{\mu_f\sqrt{3}}$$

Solving for r at $R_c = 460$ yields

$$r = \left[\left(\frac{460\mu_t}{4\rho_f} \right)^2 \left(\frac{3}{5} \right) \left(\frac{\rho_t}{\rho_s} \right) \left(\frac{1}{g} \right) \right]^{1/3} = 555 \mu m$$

Checking, at $r = 555 \mu m$ $U = 6.36$ m/s, $R_c = 460$

Three regimes of particle motion have been identified and classified according to particle radius. They are

1) Stokes Flow: $C_d = \frac{24}{R_c}$

Valid for experiments at $1g$, in air, for pocahontas coal particles
of $0 \leq r \leq 36.5 \mu m$

The scaling law here is

$$r = r' \sqrt{g'/g} \quad (\text{prime indicates orbital conditions})$$

2) Modified Oseen Flow: $C_d = \frac{24}{R_c^{2/3}}$

Valid under conditions described above for particles
of $36.5 \mu m \leq r \leq 555 \mu m$

The scaling law here is

$$r = r' \left[g'/g \right]^{3/5}$$

3) High Reynolds Number Flow: $C_d = 0.4$

Valid under conditions described above for particles
of $555 \mu m \leq r$

The scaling law here is

$$r = r' \sqrt{g'/g}$$

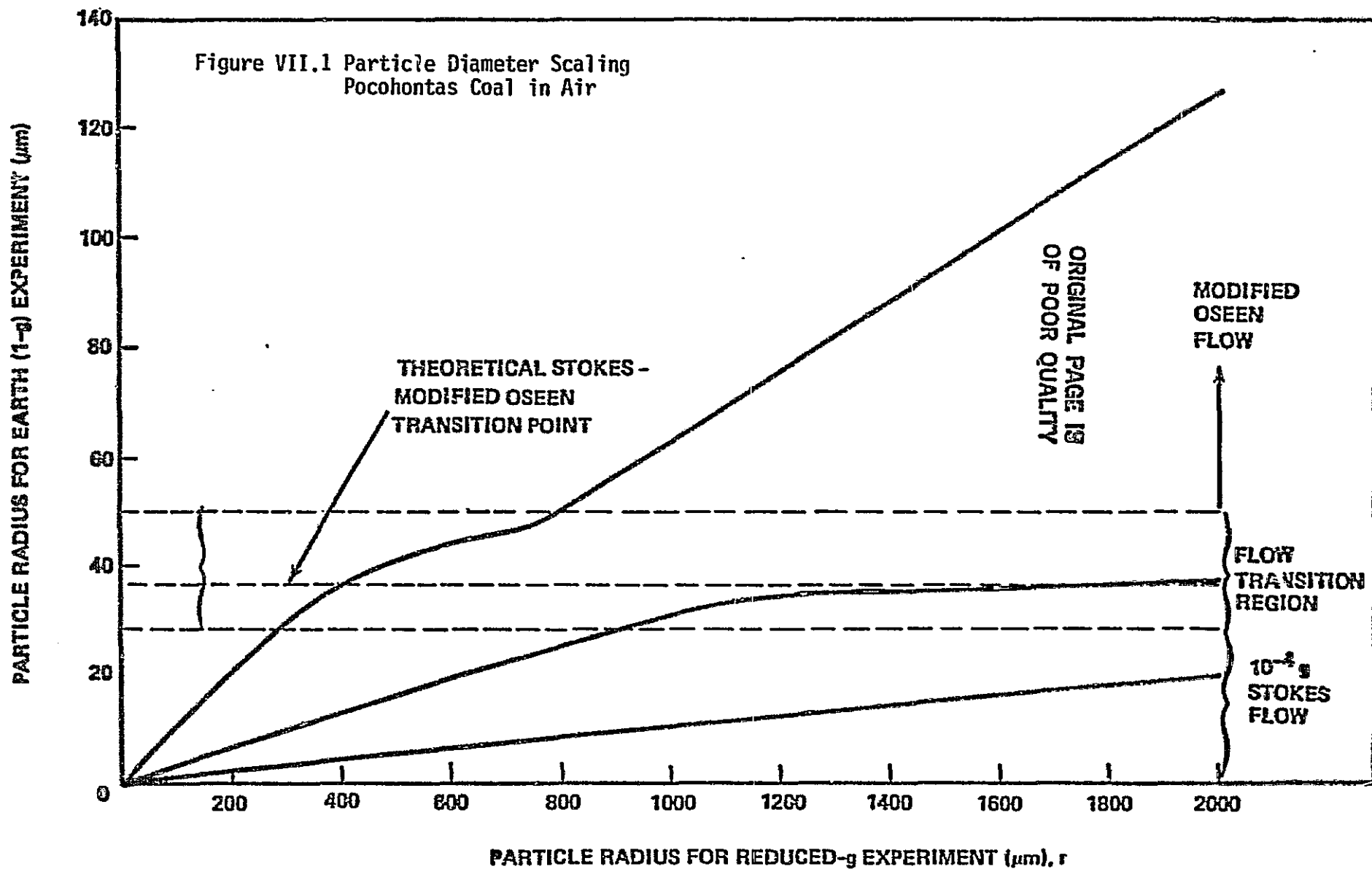
Note 1: The scaling law ranges are determined in terms of radii for the earth (1g) model. Thus to scale a 2000 μm radius particle at $10^{-2}g$, the modified Oseen relation is valid, yielding $r = 126 \mu\text{m}$

Note 2: Matching between the 3 drag regimes has been checked at 1g, condx.

$$\begin{array}{lcl}
 V_t \text{ (Stokes)} = 0.21 \text{ m/s for } r = 36.5 \mu\text{m} & \left. \vphantom{\begin{array}{l} V_t \text{ (Stokes)} = 0.21 \text{ m/s for } r = 36.5 \mu\text{m} \\ V_t \text{ (M-Oseen)} = \begin{cases} 0.21 \text{ m/s for } r = 36.5 \mu\text{m} \\ 6.3 \text{ m/s for } r = 555 \mu\text{m} \end{cases} \right\} & \text{matching} \\
 V_t \text{ (M-Oseen)} = \begin{cases} 0.21 \text{ m/s for } r = 36.5 \mu\text{m} \\ 6.3 \text{ m/s for } r = 555 \mu\text{m} \end{cases} & & \\
 V_t \text{ (Hi-Re)} = 6.3 \text{ m/s for } r = 555 \mu\text{m} & \left. \vphantom{\begin{array}{l} V_t \text{ (M-Oseen)} = \begin{cases} 0.21 \text{ m/s for } r = 36.5 \mu\text{m} \\ 6.3 \text{ m/s for } r = 555 \mu\text{m} \end{cases} \right\} & \text{matching}
 \end{array}$$

See Figure VII.1 for graphic presentation of scaling relations.

Figure VII.1 Particle Diameter Scaling
Pocohontas Coal in Air



APPENDIX 8

Analysis of Light Attenuation Levels Expected in COPSE

I) Reasons for choosing Transmission over Backscatter

- No theoretical basis for calculation of backscatter from a homogeneous volume of multiple particles.
- Backscatter is likely to be sensitive to particles near the wall (or on the wall) to the exclusion of the bulk of the volume.

II) Expected Attenuation Range ($\rho_{\text{material}} = 1.346 \text{ g/cm}^3$) for forward scatter Percent Initial Illumination Incident on Detector

Concentration mg/l	Particle Diameter (μm)		
	70	40	7.5
Maximum desirable 2000	19.1	5.5	1.9×10^{-5}
1500	28.9	11.4	9.3×10^{-4}
1000	43.7	23.5	4.4×10^{-2}
500	66.1	48.5	2.10
100	92.1	86.5	46.2
50	96.0	93.0	67.9
10	99.2	98.6	92.6
5	99.6	99.3	96.2

Table of Transmittance(%)

ORIGINAL PAGE IS
OF POOR QUALITY

Program Computes Transmittance

Store material (particle) density in Reg. 00 in g/mm^3

(Note per cubic millimeter). Density is amount of particles
in total volume in milligrams/liter

$$\frac{I_1}{I_0} = e^{-nax}$$

n = number density
A = particle area
X = path length

PRP "BEERS"

01 LBL "BEERS"
02 "MATERIAL"
03 AVIEW
04 PSE
05 "DENSITY"
06 AVIEW
07 PSE
08 "SHOULD BE"
09 AVIEW
10 PSE
11 "IN REG. 00"
12 AVIEW
13 PSE
14 "(G/MM³)"
15 "PSE"

Output is % of initial light (I_0)
transmitted.

10 "DENSITY"
19 PROMPT
20 STO 10
21 "DIA. (MIC.)"
22 PROMPT
23 1 E-3
24 *
25 STO 01
26 X+2
27 PI
28 *
29 4
30 /
31 STO 02
32 RCL 00
33 1/X
34 6
35 *
36 PI
37 /
38 RCL 01
39 -3
40 Y+Y
41 *
42 STO 03
43 RCL 10
44 *
45 1 E9
46 /
47 52 ← Part. length
48 *
49 RCL 02
50 CHS
51 *
52 E+Y
53 100
54 *
55 STO 11
56 VIEW 11
57 PSE
58 GTO "START"
59 STOP

Mapping of Particle Cloud Optical Density vs. Particle Density

Diameter range 5 → 100 μm

Density range 5 → 2000 g/l

Maximum and minimum transmittance limited by uncertainty in readings.

Percent variation, V , in one reading vs. another is

$$V_2 = \frac{n_2 - n_1}{n_1} \times 100\% \quad (\text{Variation \% at St.2 from St.1})$$

where

n_i = number density @ station i

since

$$S \propto e^{-n} \quad (S \text{ is transducer signal})$$

we have

$$V_2 = \frac{\ln \frac{S_2}{S_1}}{\ln \frac{S_2}{S_1}} - 1$$

For small attenuations (large transmittance) the Signal is # of counts less than saturation. e.g. @ saturation 100 cts. At op. point, 98 counts: Signal = 2 counts.

For large attenuations (small transmittance) the Signal is # of counts above 0. e.g. @ blackout $S = 0$, at 5% above blackout $S = 5$.

In both cases, error is # of counts. If error of 0.5 counts is assumed (0.5% precision), then to be within a 5% error bar

$$\left(\frac{\ln(S + 0.5)}{\ln(S - 0.5)} - 1 \right) \times 100 < 5$$

For any S

⇒ @ $S = 5$ cts, error = 13%

$S = 6$ cts, error = 10%

$S = 8$ cts, error = 6%

$S = 9$ cts, error = 5%

⇒ Max Signal = 91 cts.

Min Signal = 9 cts.

Thus look for locus of pts. in density/diameter space yielding

$9\% \leq \text{transmission} \leq 91\%$

$\rho_{\text{material}} = 1.346 \times 10^{-3} \text{ g/mm}^3$.

Diameter (μm)	Density @ 91% (mg/l)	Density @ 9% (mg/l)
100	165	4150
80	130	3310
60	97	2480
40	65	1660
20	32	830
10	16	415
5	8	205

NOTE

$$T = e^{-nax}$$

$$\ln T \propto nA$$

$$n \propto \text{dens}/r^3$$

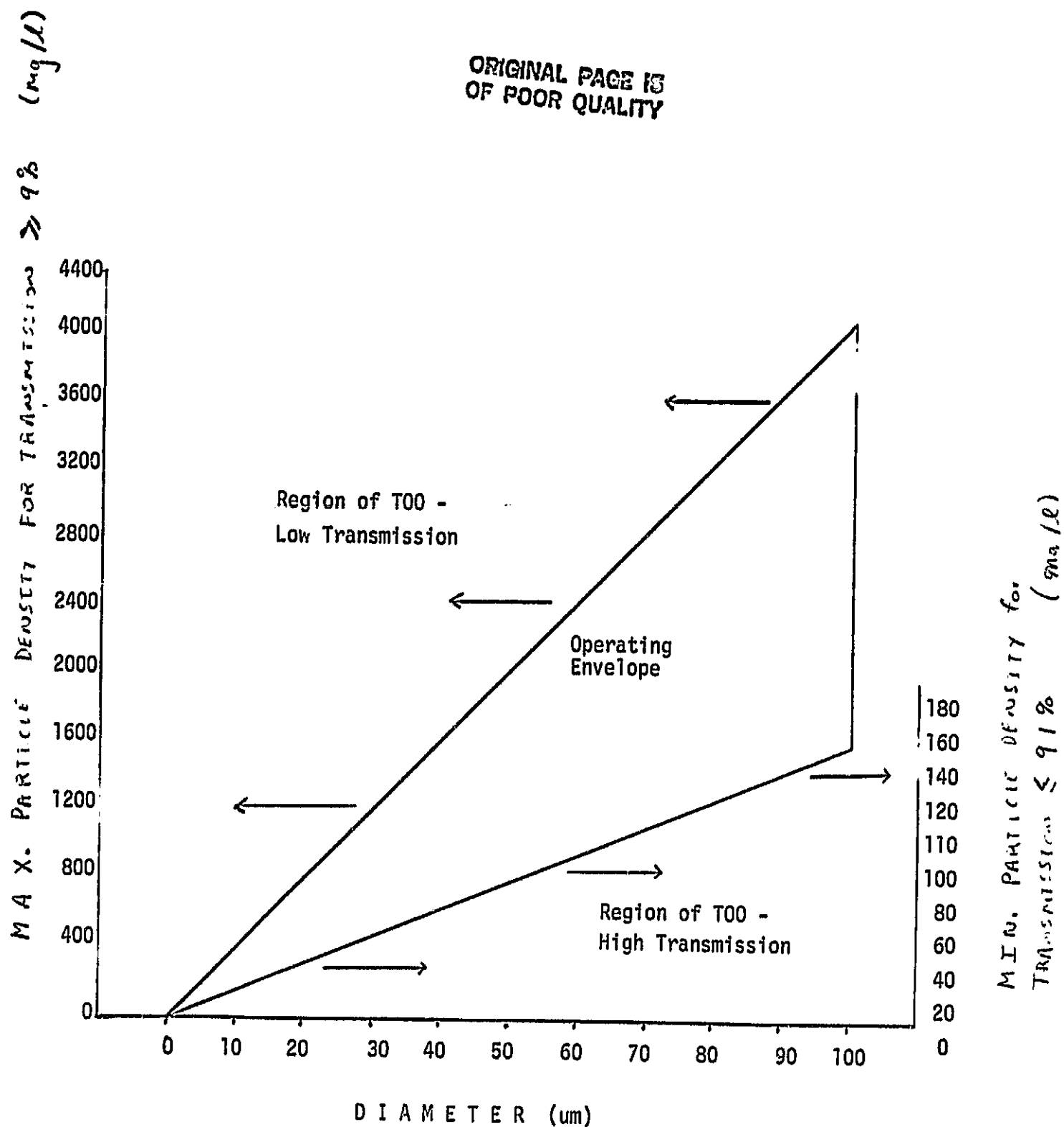
$$A \propto r^2$$

$$\Rightarrow na \propto \text{dens}/r \quad (r = \text{radius})$$

$$\Rightarrow \ln T \propto \text{density}/r$$

\Rightarrow for equal transmission (e.g. 91%) density varies proportionately with radius (or diameter).

Figure VIII.1 Operating Range of Homogeneity Detector



Total Light Loss:

Light loss is the result of

1) Wall/Air interface scattering

(air → wall → inner air → wall → air = 4 transmissions)

2) Scattering by particles 9% < transmission < 91%

3) Beam Spreading (inverse square)

Beam Spreading:

Assuming: beam spread half-angle = 15°

initial emitting area = 0.19 cm^2

illuminated area after 6 cm is 1.81 cm^2

⇒ "transmittance" = 10.5%

Wall/Air Interface:

Transmitted fraction going from a medium of $\eta = \eta_1$

into a medium of $\eta = \eta_2$ is given by

$$t = 1 - \left(\frac{\eta_1 - \eta_2}{\eta_1 + \eta_2} \right)^2$$

$\eta_{\text{lexan}} = 1.586 \Rightarrow \text{transmission} = 0.95$

over 4 interfaces the transmission is $(0.95)^4 = 0.81$

⇒ Interfacial and spreading losses account for a loss of 91% of the light produced, hence the fraction of emitted light reaching the detector is 7.7% for 91% transmission through particles varying to 0.77% for 9% transmission through particles.

A figure of 10 lumen/watt is assumed for light source efficiency.

Linear range of detector is 0 - 6 mW/cm² : light is initially in .19cm² ⇒

$$6 = (.0077) \text{ (mWemitted)}/0.19$$

⇒ an emitted radiation of 148 mW is sufficient

⇒ need ≈ 1.5 watts

3 watt bulb is sufficient.

APPENDIX 9

OGPCE - EXPERIMENTAL APPARATUS

PARTS LIST FOR SHIPMENT TO NASA, WEEK OF MARCH 21, 1983

I. BASIC TUBE ASSEMBLY AND BASE

<u>Part Label</u>	<u>Description and Number Supplied ()</u>
1	Glass Flame Tube (1)
2	Glass Flame Tube (1)
3	Flame Tube Mounting Brackets Assemblies (3)
4	Metal Base
5	Threaded Bolts for attaching B1 to B2 (6)
6	Polycarbonate Safety Shield with Aluminum Frame (1)

II. ACOUSTIC MIXER APPARATUS

7	Compression Driver (1) including Aluminum Clamp/Bracket Assembly
8	Rubber Gaskets: Small Size (3)
9	Hanger Clamps (7)
10	JBL Frequency Dividing Network (JBL Part #3010) (1)
11	Coupling Unit (1)
12	Metal Disk, 106 mm Diameter (1)
13	Rubber Gaskets (3) Large Size
14	Metal Collar (1)
15	Rubber Split Ring (1)
16	O-Ring Seals for Flame Tube (3)

III. PARTICLE INJECTION SYSTEM

17	Particle Injection Cannister (1)
18	Particle Injection Cannister (Wide) (1)
19	Al ₂ O ₃ Particles, 900 mesh 12-25 Diameter (1 Jar)
20	Glass Spheres (1 Jar)

IV. PROPELLER MIXER

21	Variable Speed Drive (1)
----	--------------------------

22 Propeller Shaft (1)
23 Bearing End Plate (1)
24 Bearing Fixed Plate (1)
25 Propeller Base Plate (1)
26-31 Propeller (1)
32 Shrouded Fan (1)

V. GAS PREPARATION, IGNITION AND VENT SYSTEMS

33 Flash Arrestor (1)
34 Spark Ignition System (1)
35 Fill-side Endplate (1)
36 Vent Plate
37 One inch tube (1)
38 Scrubber Vent System (1)
39 Borosilicate Glass Wool (1 lb. package) (1)
40 Gas Purification Cannister (1)
41 2-Liter Gas Sample Bag (1)
42 5-Liter Gas Sample Bag (1)

VI. PARTICLE, HOMOGENEITY AND FLAME-FRONT DETECTION

43 Light Source/Detection Unit (3)
44 Detector Junction Box (1)

OGPCCE - EXPERIMENTAL APPARATUS

Assembly notes for shipment to NASA, week of March 21, 1983.

I. Basic Tube and Base Assembly

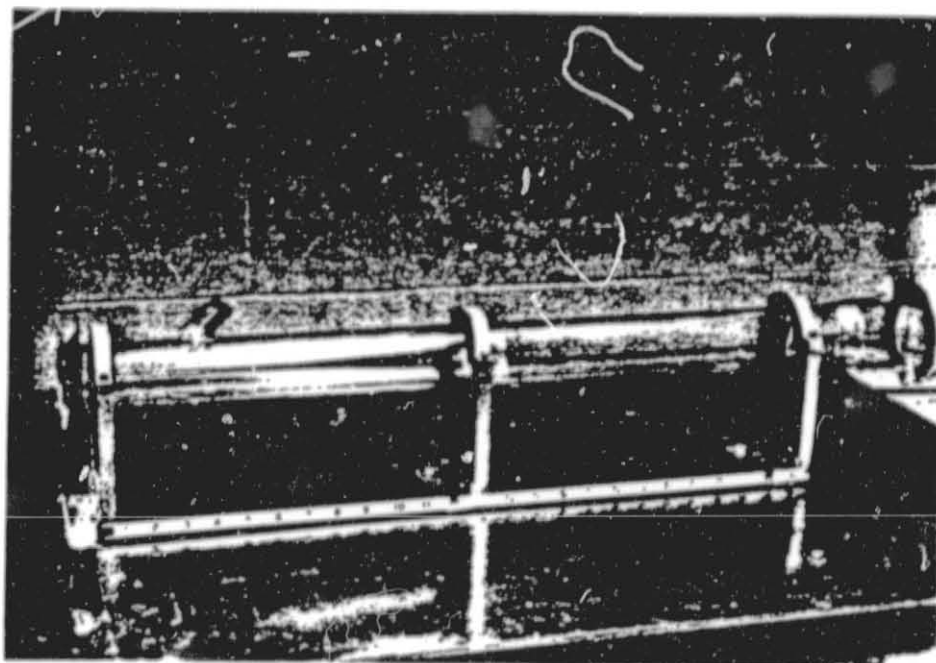


Figure 1 BASIC TUBE ASSEMBLY

Two flame tubes are supplied. #1 has a thermocouple attached to it. #2 has an improved, stronger large end fitting which will be discussed under Venting. Note that because of differences in the location and angle of the particle injector opening (shown with green rubber stopper in Fig. 1), the three brackets may need to face either left or right. This 180° rotation of a bracket shifts its clamp location by about 1". Holes for mounting these brackets are marked with letter B.

Figure 2 shows the safety shield (part #2) in place. The swinging support arms are supplied mounted on the base.

ORIGINAL PAGE IS
OF POOR QUALITY

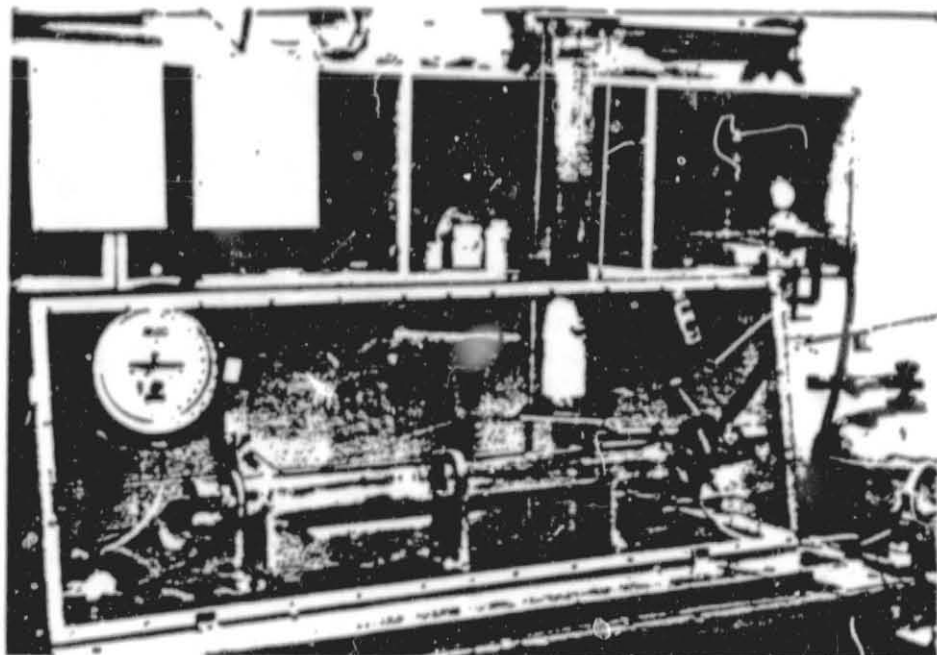


Figure 2 EXPERIMENTAL APPARATUS WITH SAFETY SHIELD IN PLACE. NOTE SUPPORTING ARMS AND L-BRACKETS

The shield is of polycarbonate material which will not shatter. It should be installed before ignition of flame tube contents. All personnel should be separated from the tube by the shield.

II. Acoustic Mixer Apparatus

The acoustic driver is shown mounted on the flame tube in Figure 3. It is supported in a clamp/bracket assembly which attaches to the base at the tapped holes marked "A". The driver is part #7. Note that while the manufacturer's marking says "8 ohms", a new coil/diaphragm has been installed of 16 ohm impedance. A label has been added correctly stating the impedance as 16 ohms.

The fitting of the driver to the tube is also shown in Figure 3. A rubber gasket (part #8) is placed between the driver and glass tube flange. A second identical gasket is placed on the other side of the glass flange. A seal is then achieved by pushing the glass tube against the tube (sliding it through brackets (part #3)). For better sealing, 3 hangar clamps (#9) are attached over the two flanges and 2 gaskets Finter Tight. Remember, you are squeezing glass so be gentle. The glass flange is not to be used to support the driver or to help squeeze the driver and tube together.

The clamps only serve to keep the gasket from vibrating and loosening.

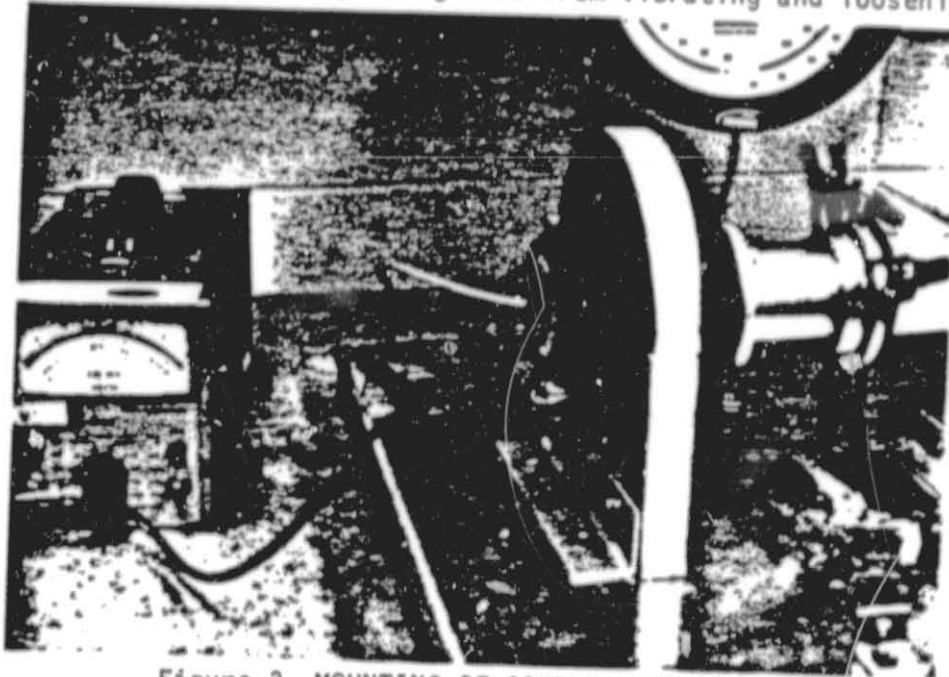


Figure 3 MOUNTING OF COMPRESSION DRIVER
AT FLAME TUBE END

A pair of devices has been provided to protect the driver from excessive signal levels and signals of low frequency (< 800 Hz) which may damage the driver. Figure 4 is a schematic diagram of their arrangement.

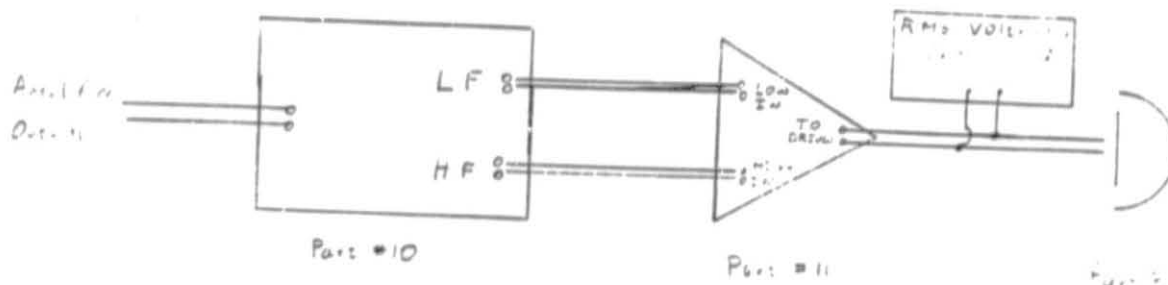


Figure 4 DRIVER SYSTEM SCHEMATIC DIAGRAM

Part #10 splits low and high frequency components of the amplified signal. The lows are fed to a resistive network in part #11. This load must be provided to ensure proper operation of part #10. The high frequency component is coupled through a 1 amp fuse to the driver. At 16 Ω impedance, a one amp fuse allows 16 watts of sine-wave power to reach the driver, which is rated at 30-35 watts sine-wave, providing a safety factor of 2. This large safety factor is necessary as the driver coil will burn out faster than the fuse. Even with this safety factor, care should be exercised to protect the speaker from high power. Do not turn on the amplifier until all connections are made to avoid switching transients. The RMS voltmeter may be used as a power meter to monitor the power input to the driver. Since

$$\begin{aligned} E &= IR && (E = \text{voltage, } I = \text{current, } R = \text{resistance}) \\ \text{and } P &= EI && (P = \text{power}) \\ \Rightarrow P &= E^2/R \end{aligned}$$

Thus, for an impedance of 16 Ω , E^2 should be kept under 480 V^2 to keep power below 30 watts. Thus, the RMS voltmeter reading should not exceed $\sqrt{480} \approx 22$ volts. Because the driver impedance is not constant at 16 Ω but is a function of frequency, a maximum of 16 RMS volts is recommended.

When performing mixing experiments, a cover must be provided at the opposite (ignition) end. This is the larger diameter opening which would be vented in combustion measurements. Figure 5 illustrates this covering which consists of the clamps (part #9), a metal disk (part #12) and two rubber gaskets (part #13), one placed between the disk and the outside of the flange, and one between the flange and the clamp. Again the fragile nature of this flange is noted.

The tube with part #2 has been remanufactured with a stronger large-end fitting. Part #14 is a metal collar and #15 is a rubber split ring which fits over that end plate. An O-ring (part #16) completes the seal. Figure 6 is a sketch of this end plate arrangement.

ORIGINAL PAGE 13
OF POOR QUALITY

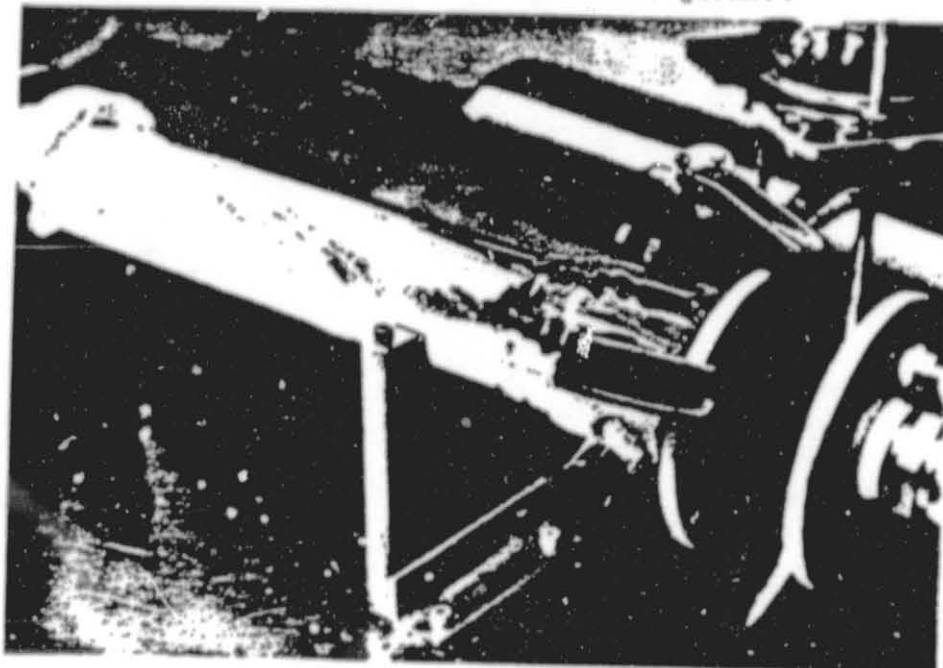


Figure 5 COVERING OF LARGE TUBE END
WITH LARGE END PLATE

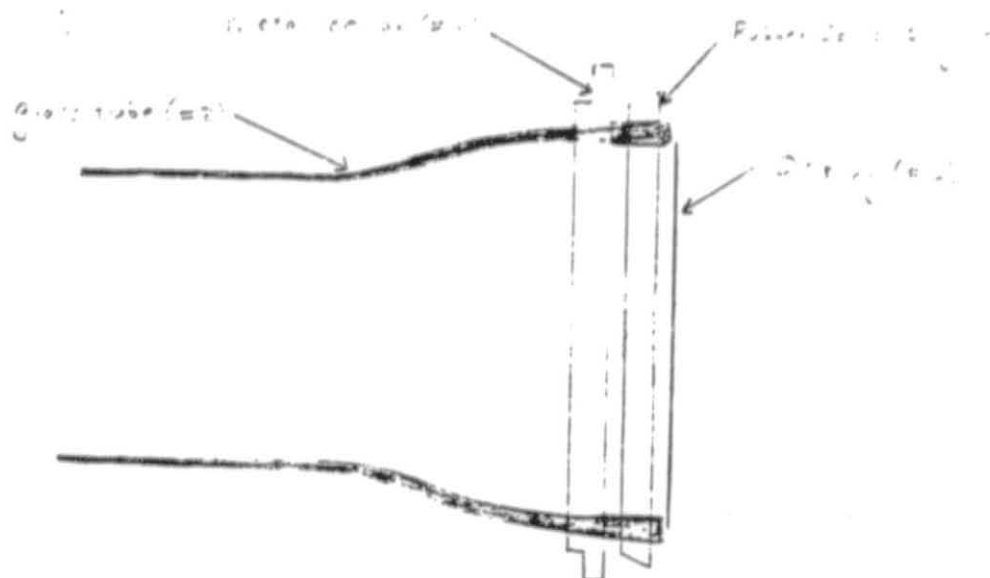


Figure 6 COLLAR AND O-RING SEAL
OF TUBE PART #2

ORIGINAL PAGE IS
OF POOR QUALITY

The 2 ports at the tube large end are for the spark ignition system electrodes which are discussed later. These may be placed in the holes for mixer testing. Otherwise rubber lab stoppers or tape should be used to close them.

The Design Manual should be consulted for overall system design and operations calculations (Acoustic mixer section IC).

The Dividing Network (part #10) controls should be set as follows:

HF Gain Control: Max

HF Boost: MAX

III. Particle Injection System

This system is shown schematically in Figure 7.

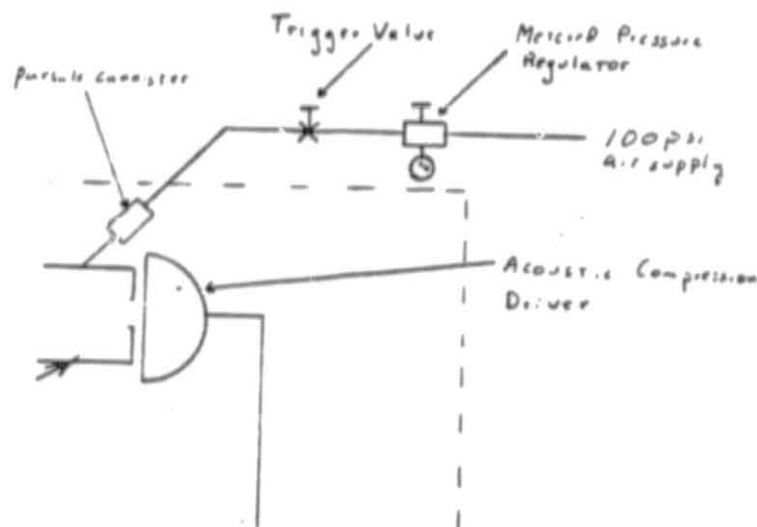


Figure 7 PARTICLE INJECTION SYSTEM

While TRW is supplying only the particle cannister, Figure 8 shows the regulator and trigger used for the test application.

The red hose is the pressurized air supply.

ORIGINAL PAGE IS
OF POOR QUALITY

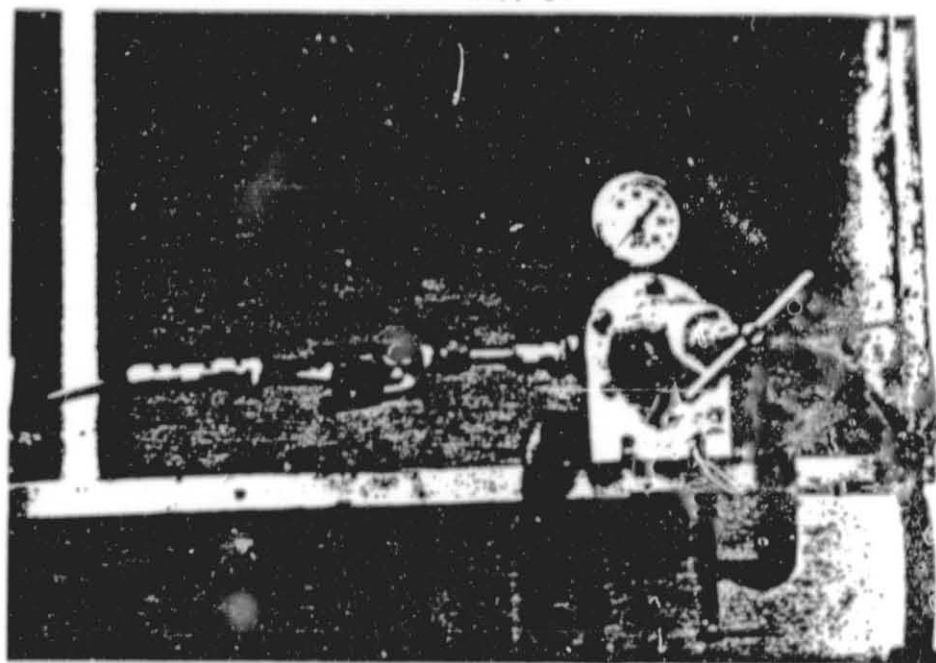


Figure 8 AIR REGULATOR AND TRIGGER

The triggered air is carried through the black line (center left) to the injection cannister shown in place in Figure 9.

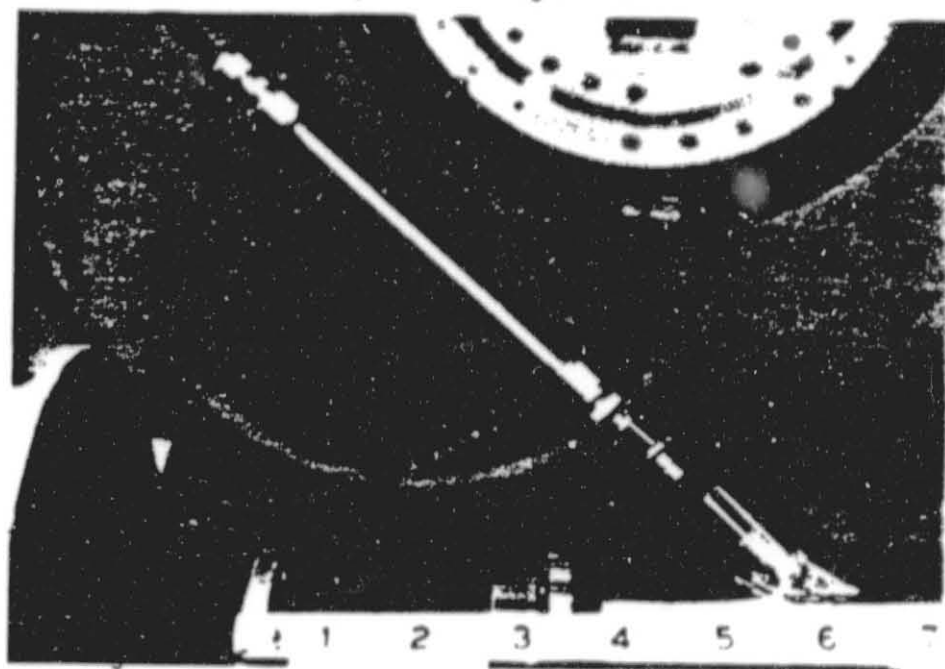


Figure 9 INJECTION CANNISTER INSTALLED ON FLAME TUBE

ORIGINAL PAGE IS
OF POOR QUALITY

The assembly of Figure 9 is part #17. An earlier version with an enlarged storage volume is part #18. Part #17 yields better performance because particles tend to become lodged in the constrictions of #18. The two parts are shown again in Figure 10. Part #17, the better performing, is in the foreground.

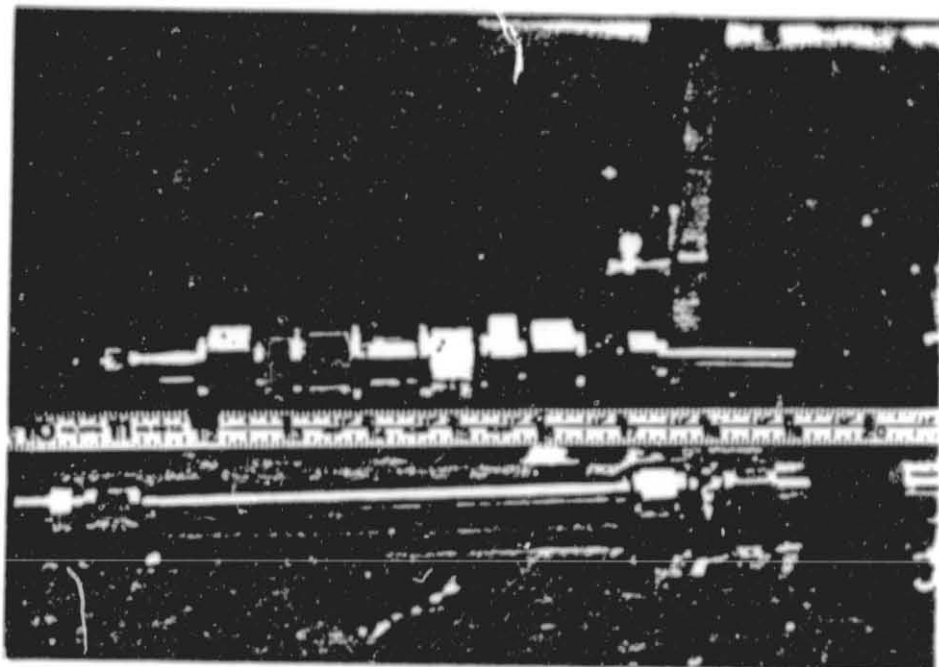


Figure 10 TWO PARTICLE INJECTION CANNISTERS

The injector works by containing particles between two teflon membranes, one at each end of the tube. These membranes are secured by AN fittings as shown in detail in Figure 11. Note that the teflon may fit either between the copper "soft-seal" and the flared tube (as shown) or between the "soft-seal" and the AN fitting. In the latter arrangement the "soft-seal" is between the flared tube and the teflon. This arrangement better protects the teflon and is preferred. A pressure of about 50 psi is adequate to rupture the two diaphragms. The diaphragms were formed of 1/2" teflon tape.

In operation, one diaphragm is assembled, the particle charge is loaded into the tube and the second diaphragm is then added.

A selection of particles is also supplied. These include: Part #19, 900 mesh Al_2O_3 particles. These were examined under a microscope and appear to be 12-25 μm in diameter. Though small they tend to agglomerate and

ORIGINAL PAGE IS
OF POOR QUALITY

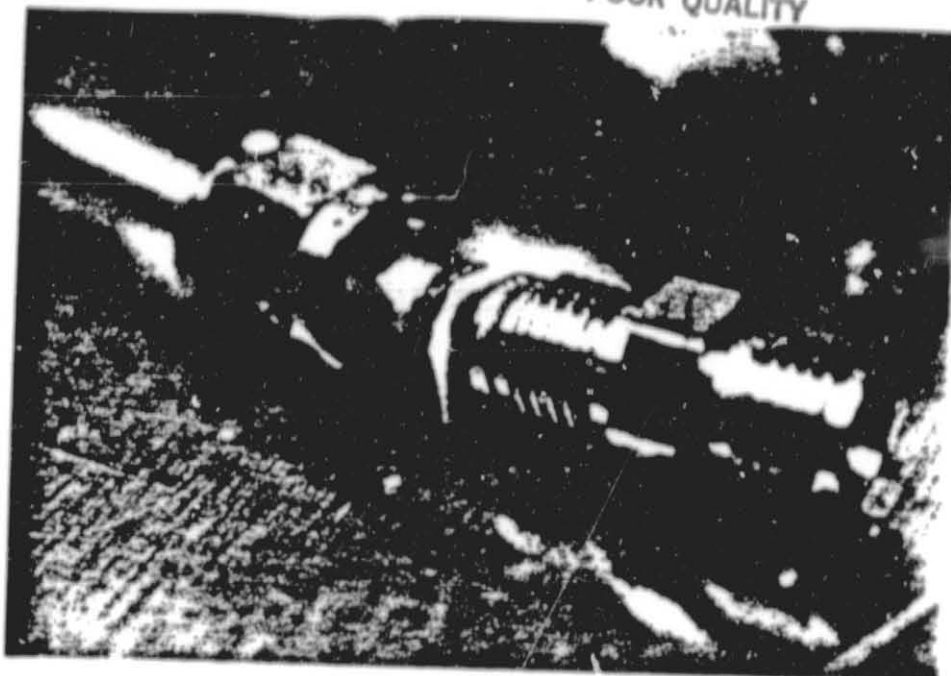


Figure 11 DETAIL OF THE TEFLON DIAPHRAGM ASSEMBLY

stick to the glass walls under mixing. Part #20; these appear to be glass ballons (i.e., hollow glass spheres). Their exact nature has not been determined and they have not been examined under a microscope. They exhibit low sink in free air and do not tend to agglomerate. They have a greatly reduced tendency to stick to glass walls. (Note how they leave the walls of their container.)

Additionally, talcum powder and corn starch have been tested. The worst performance was from the Al_2O_3 . Talc tends to adhere to walls but is very fine.

IV. Propeller Mixer

This system's schematic diagram is shown in Figure 12. The installation

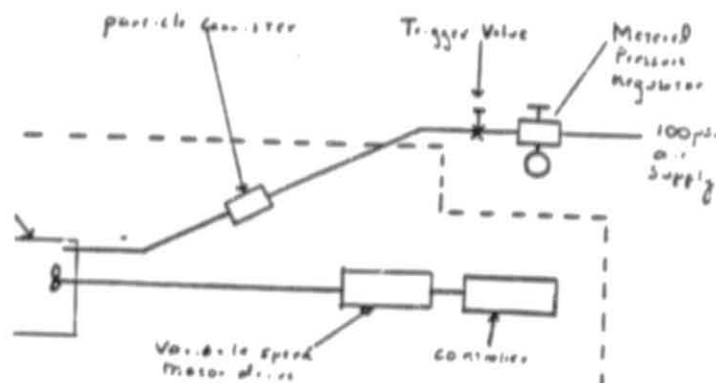


Figure 12 PROPELLER MIXER DIAGRAM

is shown in Figures 13 and 14. The variable speed drive (part #21) is attached to the propeller shaft (part #22) after the shaft has been inserted through the bearing end plate (#23) and the bearing fixed plate (#24). The fixed plate is attached to the propeller base plate (#25) which is mounted to the base (part #4) tapped holes marked p. The propeller is then attached to the shaft end between the two nuts. A number of propellers is supplied, some of which are too large to fit in the tube. These may be used by construction of a suitable shroud. Propellers are parts #26-31. In testing propellers it is recommended that particles be added while the propeller is operating. The prop mixing action is weakest at the walls where the particles will settle under 1-g conditions.

ORIGINAL PAGE 13
OF POOR QUALITY

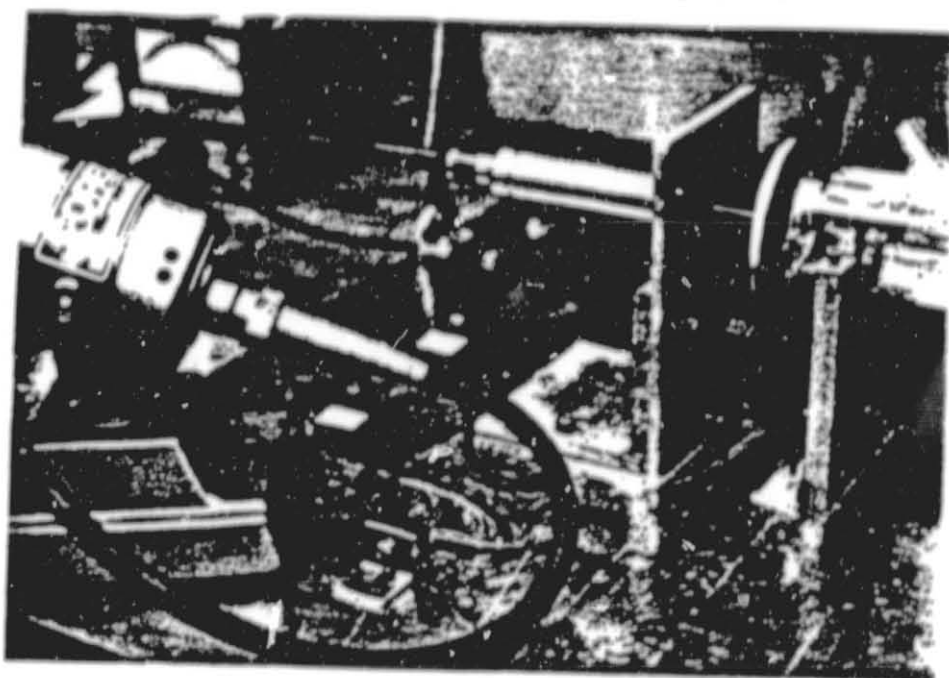


FIGURE 13 ASSEMBLY OF PROPELLER DRIVE SYSTEM

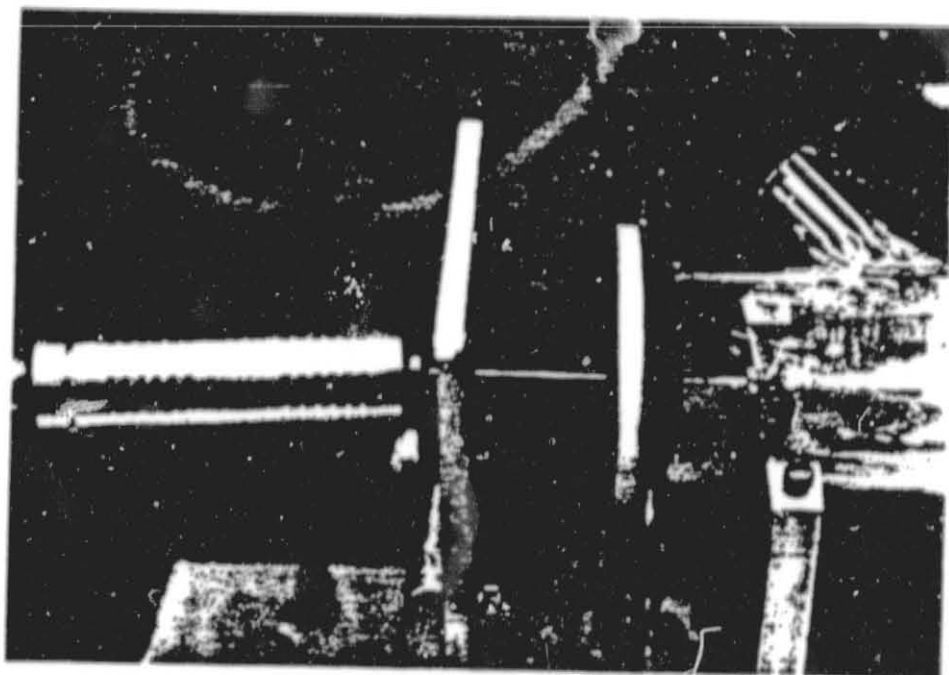


FIGURE 14 DETAIL OF PROPELLER AND SHAFT OF PROPELLER MIXER

Figure 15 depicts another propeller mixing design. The fan (part #32) is mounted on the base plate. A shroud of epoxy coated fiberglass fills the space between the fan and tube end. This shroud is now attached to the fan forming one assembly.

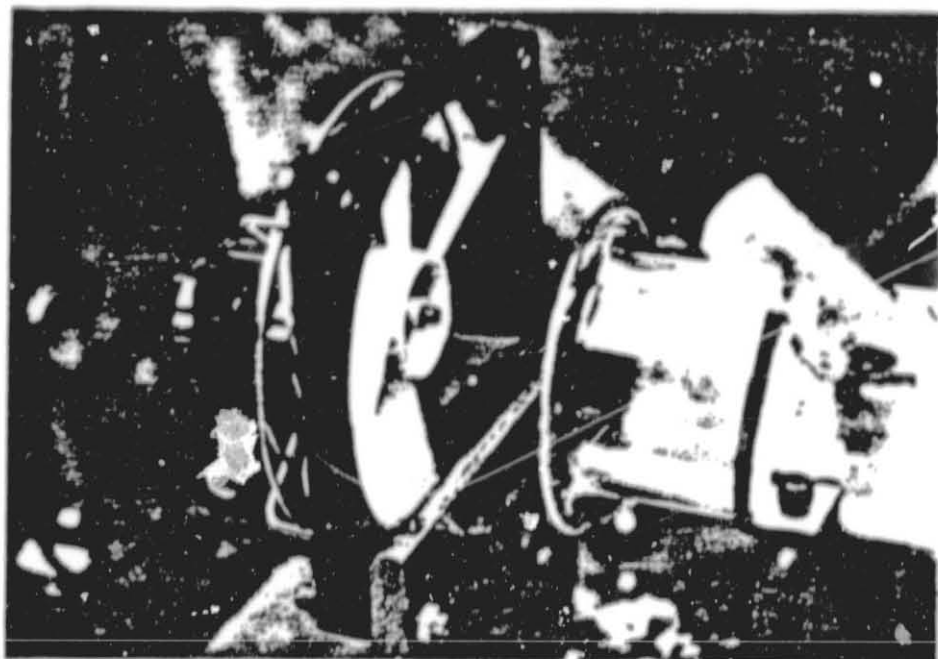


FIGURE 15 FAN MOUNTED ON PROPELLER BASE BEFORE ADDITION OF SHROUD

Again, testing is best performed by addition of particles while the fan is operating.

V. Gas Preparation, Ignition and Vent Systems

Gas mixtures were prepared by partial pressure in a mixing bottle fitted with a 0-100 psia gauge. A flash arrestor (part #33) was fitted to the bottle. During filling the arrestor is mounted so that the arrows indicating flow direction point into the mixture bottle. The arrestor is then reversed when used to form part of the flame tube filling circuit. Figure 16 shows the fill/mixture preparation system. Note that the flame arrestor serves as a check valve as well.

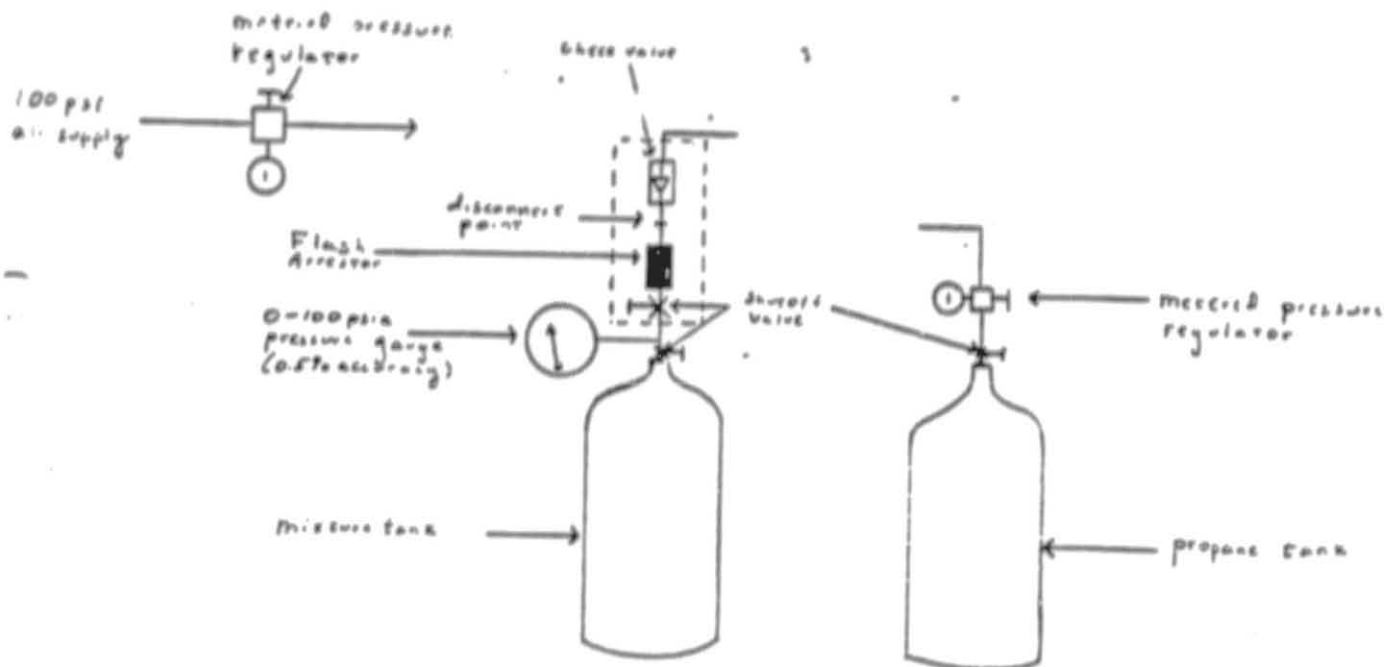


FIGURE 16 MIXTURE PREPARATION SYSTEM

Ignition of gas mixtures is by spark discharge between two copper electrodes. The system is supplied as 1 unit, part number 34. Eight to 12 volts are applied to the front panel plug from a supply capable of delivering 6 Amperes. After turning the rocker switch to "on" momentarily depressing the push-button switch and then releasing it results in a high voltage discharge.

ORIGINAL PAGE IS
OF POOR QUALITY.

The two electrodes are held in place by the black rubber stoppers which are inserted through opposing fittings in the large end of the flame tube. They are shown installed in the lower right side of Figure 2. A spacing of 1-2 cm gives reliable sparking. Figure 17 is a diagram of the spark circuit

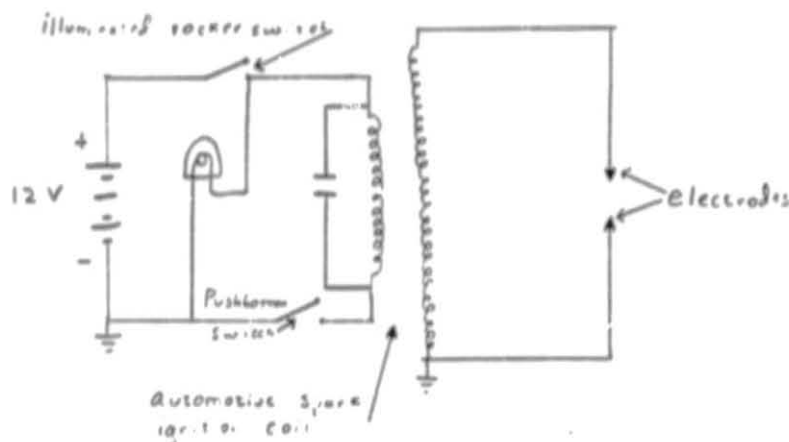


Figure 17 SPARK IGNITION CIRCUIT

Very high voltages are produced between the electrodes. Caution should be used in the operation of the device.

When preparing for ignition tests, the fill-side endplate, part #35, should be installed at the small end of the tube. This part has a swagelock fitting for purging and filling the tube and a 10 psi pop valve to guard against shattering of the glass tube in case of an overpressure caused, for example, by a blockage of the vent system. This plate is shown mounted in Figure 18.

Before ignition, the opposite (large) tube end should be fitted with a vent system. This connection is made using the vent plate, part #36. This plate is provided with a 1 inch fitting for attachment to a vent system and a swagelock fitting for a pressure transducer.

ORIGINAL PAGE IS
OF POOR QUALITY

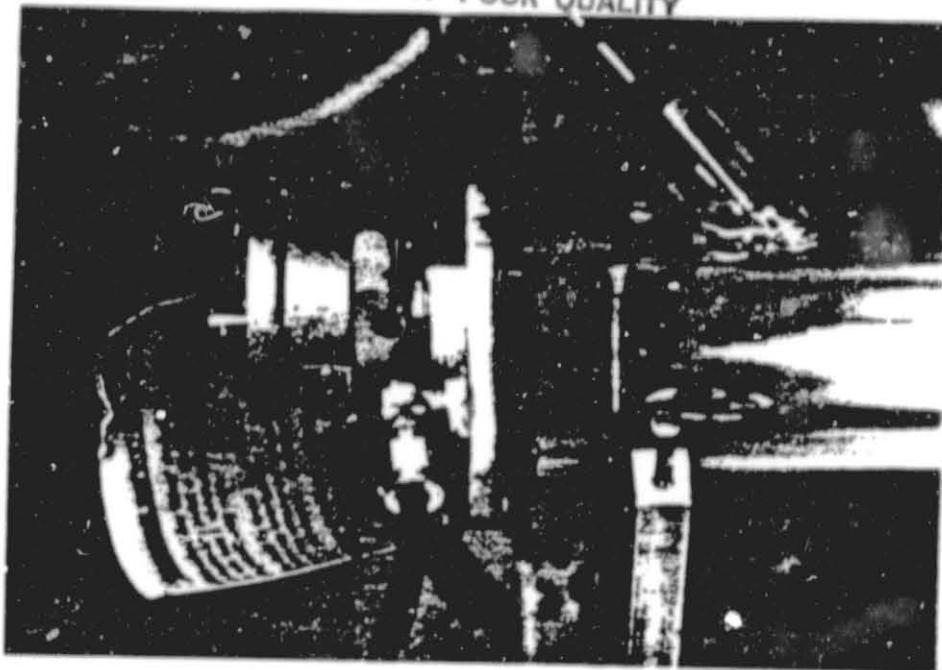


FIGURE 18 FILL SIDE ENDPLATE INSTALLATION: NOTE FILL LINE FROM MIXTURE BOTTLE AND 10 PSI (SAFETY) VALVE. THE PARTICLE INJECTION PASSAGE IS BLOCKED WITH THE GREEN RUBBER STOPPER.

In the anticipated Space Transportation System installation, this end of the tube may be too close to the wall of the enclosure to allow placement of a vent system. The 1 inch tube (part #37) would be used to carry exhaust gases to whichever vent system is chosen. It is packed with glass wool to prevent flame propagation in it and to help cool the exhaust gas. Do not attempt to support this tube with the end plate (#36) when in turn supporting the end plate on the glass tube. This will result in cracking the glass tube. Be sure the tube and end plate are resting on other laboratory apparatus. Figures 19 and 20 show the end plate and tube mounted to the scrubber vent system discussed below.

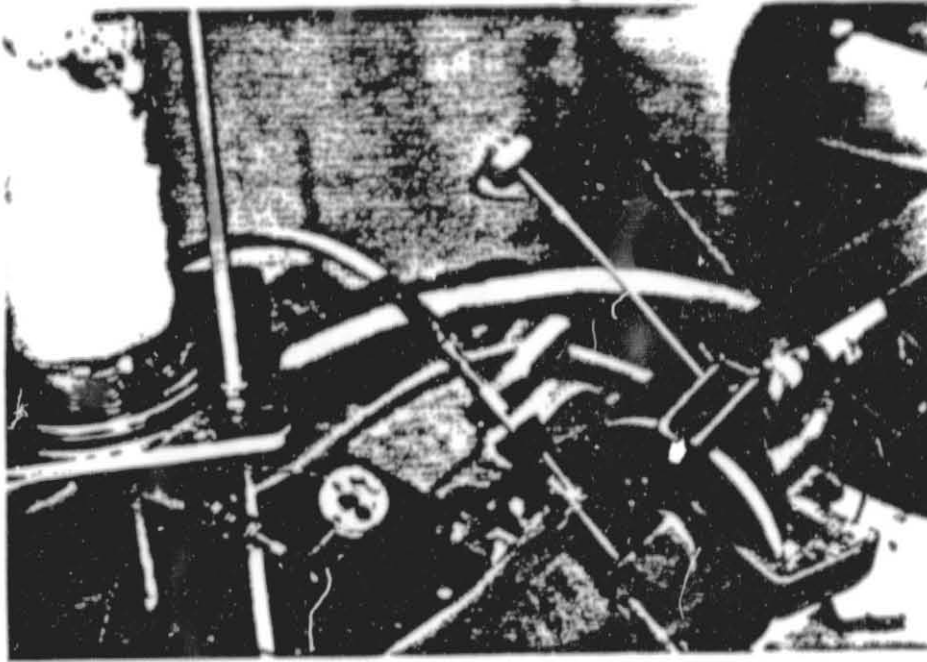


FIGURE 19 INSTALLATION OF THE VENT PLATE AND ONE-INCH TUBE AT THE FLAME TUBE. SUPPORT OF THIS HARDWARE IS FROM THE BASE OF THE SCRUBBER VENT IN THE LEFT SIDE OF THE PICTURE. WITH THE GLASS FLAME TUBE REMOVED, THE TUBE AND END PLATE DO NOT SAG. THEY ARE SUPPORTED BY TIGHTENING THE TUBE AT THE VENT BASE.

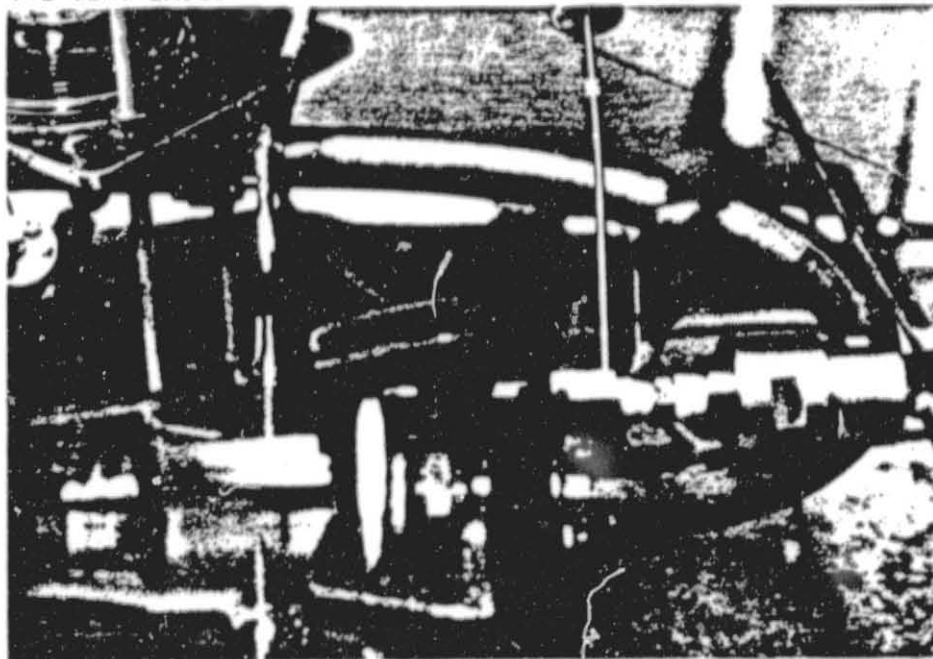


FIGURE 20 SIDE VIEW OF THE VENT PLATE AND TUBE INSTALLATION. THE PRESSURE TRANSDUCER IS MOUNTED DIRECTLY ABOVE THE 1-INCH TUBE.

The scrubber vent system (part #38) consists of a packed glass tube, a pair of end plates and mounting hardware. It is also fitted with thermocouples for the inlet and outlet flows. Figure 21 shows it mounted into the base plate (part #4) at the holes marked VN and V. The holes marked VN are backed with nuts to further secure the system.

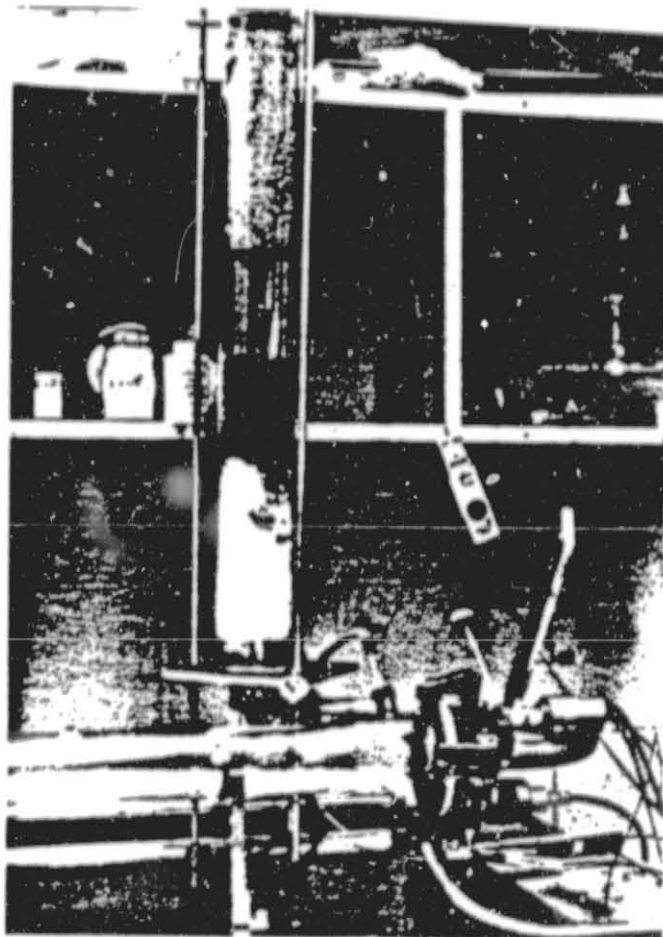


FIGURE 21 INSTALLATION OF THE SCRUBBER VENT SYSTEM

At the base of the scrubber is a fitting to attach to the one inch tube and a steel tube with a plastic cover. This tube is to bring fresh air into the scrubber and should be uncapped for use. The three scrubber layers are: glass wool (borosilicate glass) for particulate filtering and cooling; a molecular sieve for drying exhaust gas and Hopkalite, a material for catalyzing the reaction of CO and O_2 to CO_2 . Note that these materials must be kept in sealed containers so that they do not become saturated.

ORIGINAL PAGE IS
OF POOR QUALITY

For this reason the bottom fitting has a rubber stopper, the steel rod has a plastic cover and the upper vent hole is covered with rubber sheet. These three covers should be removed for operation. The steel rod is partially packed with glass wool (part #39) to prevent the granular material from spilling through it should it be tipped. Nonetheless, care should be taken to keep the vent vertical. The molecular sieve and catalyst materials were taken from a gas purification cannister. A second such cannister is supplied (#40).

Venting into balloons may be tested using the gas sampling bags provided. A 2-liter and a 5-liter balloon are provided (part #41 and 42 respectively). These bags are opened by cutting as shown on the bag. They may be attached to the tube (#37) with a rubber band, tape, or a rubber o-ring.

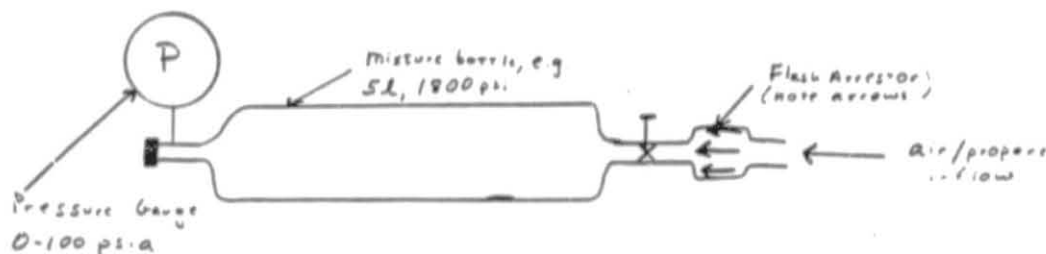
The procedures used at TRW for mixture preparation and flame tube filling are reproduced below.

These are supplied for examples only. The precise fill procedure should be developed by the hardware and requirements at LeRC.

Example Mixture Preparation Procedure:

CAUTION: Work behind safety shield
Wear eye protection
No open sparks or flames
All electrical equipment OFF

- 1) Configure mixing tube as per diagram A



(Diagram A)

- 2) Crack connection between bottle and pressure gauge.
- 3) Connect lab air (compressed) to flash arrestor inlet.
- 4) Flush system with lab compressed air.
- 5) Tighten bottle/gauge connection.
- 6) Fill bottle with lab air to $p \leq 80$ psia.
- 7) Shut valve, disconnect lab air, connect propane at inlet to flush arrestor (do not tighten).
- 8) Purge propane line.
- 9) Tighten propane line and regulate to $p > 90$ psia.
- 10) Open valve to permit propane entry. For stoichiometric, partial pressures are 96% air to 4% propane.
- 11) Close valve, shut off propane.
- 12) Reverse flash arrestor to permit flame tube filling.

Flame Tube Purge/Fill Procedure:

CAUTION: Work behind safety shield
Wear eye protection
No open flames or sparks
Power supply located far from experiment
All OTHER electrical equipment off
Ensure adequate ventilation

Configure flame tube as per diagram B

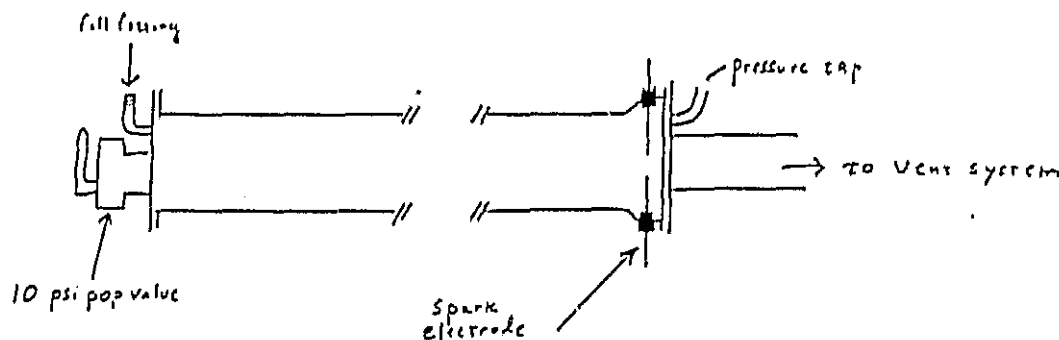


Diagram B

- 1) Connect the exit from the flash arrestor to the fill fitting.
- 2) Purge system by flowing inflammable (propane/air) mixture.
NOTE: Purge flow will enter vent system. If this is undesirable, disconnect vent system first.
- 3) Disconnect propane/air line from fill fitting and cover with nut.
- 4) Reconnect vent system if necessary (see step 2).
- 5) Ignite with spark.

VI. Particle Homogeneity and Flamefront Detection

Three light source/detector units are supplied (part #43). The detector portion is used alone for flame front detection, while its response to its associated light is used for particle homogeneity measurement. These units are slipped (carefully) over the flame tube at the desired location. The lines are connected to the marked plugs on the detector junction box, part #44. Each detector is shunted by a potentiometer in the junction box. The potentiometers are adjusted by the "detector loading" control. In this way, the three responses may be balanced before initiation of a test. This shunting also prevents detector voltage saturation which occurs at very low light levels when input directly to high impedance devices without shunting. The detectors are Archer (Radio Shack) catalog number 276-144. Further information on the operation of these devices is available in the design manual. Note that because of the detectors used, no external power supply is required. The output recorded (at the plugs marked "strip chart output") as a function of power applied to a single light by measure of the voltage across it and current through it is tabulated in Table 1.

TABLE 1 DETECTOR PERFORMANCE MEASUREMENT

Power Supplied to 1 Light Bulb/mW	Voltage Output (mV) (Shunt Value 1740 Ω)	(Shunt Value 200 Ω)
0	0	0
55	0	0
110	1.2	0
180	10.8	1.2
280	43.6	5.0
365	83.1	9.7
450	133.3	15.7
660	180.3	21.7

APPENDIX 10

[illegible]

ORIGINAL PAGE IS
OF POOR QUALITY

PAYLOAD HAZARD REPORT		NO. PCCE -1
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Electrical		DATE 13 December 1982
HAZARD TYPE Fire - Ignition Sources		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), Paragraph 213, Electrical Systems		
DESCRIPTION OF HAZARD: Short circuit, electrical sparks, electrical or mechanical failures causing high temperature buildup within vicinity of flammable atmospheres resulting in ignition of flammable atmosphere and the production of smoke, contaminants, toxic fumes and fire.		
HAZARD CAUSES: <ol style="list-style-type: none"> 1. Short circuits 2. Circuit overloads 3. Mechanical component freezing up or failing 4. Arching or sparking 5. Poor grounding 6. Use of flammable material in conjunction with electric motors 		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

ORIGINAL PAGE IS
OF POOR QUALITY

PAYLOAD HAZARD REPORT		NO. PCCE-2
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Electrical		DATE 13 December 1982
HAZARD TITLE Fire Propagation		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements Using the Space Transportation System (STS), Paragraphs 209, Hazardous Materials #3 Flammable Materials page 206,		
DESCRIPTION OF HAZARD: Inadvertant propagation of fire due to fan circulation of air or due to use of hazardous materials		
HAZARD CAUSES: 1. Fan Control(s) failure 2. Presence of hazard materials - materials of construction film		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

PAYLOAD HAZARD REPORT		NO. PCCE-3
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Environmental Control		DATE 13 December 1982
HAZARD TITLE Contamination - Toxic Fumes and Particles		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraph 201, Failure Tolerance.		
DESCRIPTION OF HAZARD: Failure of experimental container to isolate combustion particles and combustion generated toxic and odorous fumes from the manned environment.		
HAZARD CAUSES: 1. Faulty, non-redundant seals 2. Shattering of experimental container 3. Materials now available such as lycopodium which support growth of fungus		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

PAYLOAD HAZARD REPORT		NO. PCCE-5
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Human Factors		DATE 13 December 1982
HAZARD TITLE Excessive Noise		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraph 214, Verification Requirements.		
DESCRIPTION OF HAZARD: Injury to flight personnel due to equipment producing noise levels in excess of TBD dB.		
HAZARD CAUSES: 1. Payload elements exceeding the noise criteria standards in MSFC-STD-512.		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

PAYLOAD HAZARD REPORT		NO. PCCE-6
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Human Factors		DATE 13 December 1982
HAZARD TYPE Contamination - offgassing		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), Paragraph 209, Materials: Material Offgassing		
DESCRIPTION OF HAZARD: Release of flammable and/or toxic material environment due to offgassing from components		
HAZARD CAUSES: 1. Offgassing of experiment materials <div style="text-align: right;">ORIGINAL PAGE IS OF POOR QUALITY</div>		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

ORIGINAL PAGE 13
OF POOR QUALITY

PAYLOAD HAZARD REPORT		PCCE-7
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Human Factors		DATE 13 December 1982
HAZARD TITLE Electrical Shock - General		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraphs 201, Failure Tolerance and 213, Electrical Systems.		
DESCRIPTION OF HAZARD: Injury to flight personnel due to electric shock during contact with control panel.		
HAZARD CAUSES: 1. Improperly secured or vibrated loose connectors. 2. Defective connectors. 3. Improper grounding. 4. Improper fusing.		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

PAYLOAD HAZARD REPORT		NO. PCCE -9
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Human Factors		DATE 13 December 1982
HAZARD TITLE Contamination - Release of Shatterable Particles to Manned Environment		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraphs 201, Failure Tolerance and 206, Failure Propagation.		
DESCRIPTION OF HAZARD: Shattering of glass lenses, combustion particle containers, and light bulbs by temperature transients, vibration and collision, causing injury to personnel.		
HAZARD CAUSES: <ol style="list-style-type: none"> 1. Changes in temperature which could cause fracture 2. Defective parts 3. Shock during ground loading 4. Unshielded shatterable materials 5. Launch and entry environment 		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

ORIGINAL PAGE 13
OF POOR QUALITY

PAYLOAD HAZARD REPORT		NO. PCCE-10
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Materials		DATE 13 December 1982
HAZARD TITLE Stress Corrosion Induced Failures		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraph 208.3, Stress Corrosion.		
DESCRIPTION OF HAZARD: Failure of metal structures and parts due to stress (intergranular) corrosion allowing weakened structures to become flying projectiles.		
HAZARD CAUSES: 1. Use of materials not meeting the requirements of MSFC-SPEC-522A. 2. Manufacturing stresses.		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

PAYLOAD HAZARD REPORT		NO. PCCE- 15
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Optical		DATE 13 December 1982
HAZARD TITLE Injury - Laser Light Exposure		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraph 212, Radiation.		
DESCRIPTION OF HAZARD: Exposure of ocular components to subthreshold laser intensities allowing the accumulation of ocular component damage or increased susceptibility to allow damage.		
HAZARD CAUSES: <ol style="list-style-type: none"> 1. Exposed laser light sources. 2. Inadequate limit stops and shields. 3. Laser radiation exposure exceeding the maximum permissible exposure criteria given in ANSI Z 136.1-1980, American National Standard for the Safe Use of Lasers. 		
HAZARD CONTROLS: ORIGINAL PAGE IS OF POOR QUALITY		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

ORIGINAL PAGE IS
OF POOR QUALITY

PAYLOAD HAZARD REPORT		NO. PCCE-17
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Pressure Systems		DATE 13 December 1982
HAZARD TITLE Explosion - Pressure Vessel		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraph 208.4, Pressure Vessels.		
DESCRIPTION OF HAZARD: Explosion of air bottle pressure vessel due to a temperature increase, impact, vibration or acceleration induced loads causing shuttle damage and injury to personnel.		
HAZARD CAUSES: 1. Inadequate shielding of pressure vessels 2. Inadequate pressure vessel restraining devices 3. Over-pressure vessel 4. Over-temperature vessel		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS:		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

PAYLOAD HAZARD REPORT		NO. PCCE -19
PAYLOAD Particle Cloud Combustion Experiment		PHASE 0
SUBSYSTEM Structures		DATE 13 December 1982
HAZARD TITLE Structural Failures		
APPLICABLE SAFETY REQUIREMENTS: NHB 1700.7A, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), paragraphs 208.1, Structural Design and 208.2, Emergency Landing Loads.		
DESCRIPTION OF HAZARD: Injury to personnel caused by failed structures or securing hardware allowing objects to become projectiles.		
HAZARD CAUSES: 1. Appropriate safety factors not applied 2. Propagation of a pre-existing flaw in the materials used 3. Improper location of c.g. or overload of locker volume		
HAZARD CONTROLS:		
SAFETY VERIFICATION METHODS: <div style="text-align: center;">ORIGINAL PAGE IS OF POOR QUALITY</div>		
STATUS:		
CONCURRENCE	PHASE I	PHASE II
Payload Organization		
STS Operator		
APPROVAL	PHASE III	
Payload Organization	STS Operator	

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
PCCE (PARTICLE CLOUD COMBUSTION EXPERIMENT)
PHASE 0 SAFETY REVIEW
MINUTES OF MEETING
APRIL 20, 1983

The PCCE phase 0 safety review was held in building 45, room 651, at 9:00 a.m. Those in attendance were:

JSC

CA6/D. A. Ballard
DH6/B. Sellari
ER/H. A. Kuehnel
LN/M. M. Lusk
LP/C. E. Chassay
NS2/M. P. Fodroci (Boeing/HS-04)
NS2/S. M. Luczkowski
NS2/D. S. Noah
NS2/E. J. Schlei
NS2/B. G. Walker (Boeing/HS-04)
WA3/J. D. Loh

TRW

J. Kropp

LeRC

501-7/T. Labus
501-7/R. C. Nussle

1. General. Mr. Noah opened the meeting by introducing the attendees. Mr. Nussle started the discussion by describing the payload. In the course of the discussion, several changes to the experiment concepts described in the phase 0 safety data package were announced:

✓ a. There will not be an electric motor to turn the carousel; instead, a crewmember will turn it manually.

b. The present design vents the products of combustion to an expandable metal balloon. Two other options were discussed during the review. TRW suggested venting the products through a filter that would be open at the opposite end to the cabin atmosphere. It was suggested to LeRC that using the overboard dump system of the waste management system could be a viable possibility. These options will be studied, and a design or procedure will be selected prior to the phase I safety review.

✓ c. Instead of using a single tank to store pressurized air, each flame tube may have its own individual air cartridge to provide macroscopic mixing.

It was suggested that CO₂ (carbon dioxide) cartridges could be used if they were emptied and backfilled with air at 100 psi. It was estimated that each of the cartridges would contain 190 joules of stored energy. The Lexan (polycarbonate) flame tubes have an operating pressure of 120 psi and a burst pressure of 500 psi. During normal experiment combustion, the pressure rise in each tube is less than 2 atmospheres (approximately 30 psi).

The payload organization stated that there would be no batteries for this experiment. They also stated that the frequency of the acoustic mixer is planned to be in the range of 1 to 5 kHz. The present plan for the ignition system uses a condenser coil and a spark plug type igniter. Other ignition systems are being considered.

A discussion followed on the potential hazard of explosion when burning fuel dust. Grinding a fuel into dust greatly increases the combustible surface area, and a high enough concentration of dust could result in a rapid evolution of gas accompanied by an explosive pressure rise. LeRC was assigned action item 1 (see attachment) to assess the explosion hazard potential, and to describe the controls that will be implemented. LeRC was also assigned action item 2 to determine the total amount of fuel and to provide a toxicity assessment of the fuels and their combustible byproducts.

2. HR (Hazard Report) Review. When the discussion of the various design options was completed, the following HR's were reviewed. Mr. Schlei pointed out that there was no HR addressing EMI (electromagnetic interference). LeRC was assigned action item 3 to prepare an HR on EMI.

a. PCC-1, Fire, Ignition of Flammable Atmosphere. The hazard title should be changed to "Fire, Ignition Sources." In the applicable safety requirements section, the words "paragraph 219, Flammable Atmosphere" should be deleted and replaced by the words "paragraph 213, Electrical Systems."

b. PCCE-2. This HR should be rewritten to address flammable materials in accordance with NHB 1700.7A, "Safety Policy and Requirements For Payloads Using the Space Transportation System (STS)," paragraph 209.

c. PCCE-3, Contamination-Toxic Fumes and Particles. Add information concerning any biological growth hazards associated with Lycopodium.

d. PCCE-5, Excessive Noise. This HR was acceptable for phase 0.

e. PCCE-6, Contamination-Release of Flammable, Toxic and Shattered Materials. Change title to "Contamination-Offgassing." Move the discussion of shatterable materials to PCCE-9.

f. PCCE-7, Electrical Shock-General. This HR was acceptable for phase 0.

g. PCCE-8, Injury-General. Modify the hazard description to include crew contact with high temperature surfaces.

h. PCCE-9, Contamination-Release of Glass Particles to a Manned Environment. This HR should be modified to address both launch and reentry hazard.

i. PCCE-10, Stress Corrosion Induced Failures. This HR was acceptable for phase 0.

j. PCCE-12, Contamination-Film. Delete this HR and add film flammability concerns to PCCE-2.

k. PCCE-13, Contamination-Electric Motors. Delete this HR and add concerns associated with electric motor ignition sources on PCCE-1. Materials concerns should be addressed on PCCE-2.

l. PCCE-15, Injury-Laser Light Exposure. This HR was acceptable for phase 0.

m. PCCE-17, Explosion Pressure Vessel. This HR was acceptable for phase 0.

n. PCCE-19, Projectiles. Change the hazard title from "Projectiles" to "Structural Failure."

o. PCCE-20, Improper Adapter Plate Loading. Delete this HR and include the concerns on PCCE-19

3. Conclusion. The PCCE phase 0 safety review is considered complete. All action items and HR modifications are due at the phase I safety review. The date for the phase I safety review has not been determined.

ORIGINAL PAGE 19
OF POOR QUALITY

NS2/83-L215

Distribution

KSC, CP-PCO/W. E. Paramore
SF-ENG/C. R. Billings
JSC, DA6/D. A. Ballard
ER/H. A. Kuehnel
LN/M. M. Lusk
NS2/B. J. Miller
SD3/J. M. Waligora
MA/R. A. Colonna
WA3/J. D. Lobb

ORIGINAL PAGE IS
OF POOR QUALITY

cc: (*w/encl.)

NASA Hqs., D/H. Cohen

*DP/P. D. Davis

MCB-7/C. M. Lee

KSC, CP/J. J. Neilon
CP-PCO/W. E. Paramore
SF-ENG/C. R. Billings
SP-FGS/F. Harper
VT/E. Johnson

JSC, CB/J. W. Young
*DH6/B. Sellari
FA/J. C. Bostick
LA/G. S. Lunney
LA6/L. S. Nicholson
LA6/L. G. Williams
LK/A. E. Morse, Jr.
LP/R. A. Moke

*LP/C. E. Chassay

NA/M. L. Raines

NB/J. H. Levine

NB5/R. H. Steele

NS/J. B. Hammack

*NS/W. T. Mays (Boeing/HS-04)

*NS2/M. P. Fodroci (Boeing/HS-04)

*NS2/B. G. Walker (Boeing/HS-04)

NS2/W. C. Powell (Boeing/HS-04)

NS2/B. Dugdale (Boeing/HS-04)

*NS2/S. M. Luczkowski

*NS2/D. S. Noah

*NS2/E. J. Schlei

LeRC, *501-7/T. Labus

*501-7/R. C. Nussle

TRW, Inc.

Attn: *Mr. Jack Kropp

Bldg. R-1/2162

One Space Park

Redondo Beach, CA 90278

DATE 4/20/83

SAFETY REVIEW ACTIONS

PAYLOAD PCCEREVIEW PHASE 0

ACTION NUMBER	ASSIGNEE	TASK	ACTION DUE	REQUESTER	ACTION RESPONSE	CLOSEOUT DATE
1	LeRC/R. Nussle	Determine whether the worst-case mixtures of fuel and air could result in an explosion. Assess the ability of the flame tubes to withstand an explosion. Describe the controls available which prevent an explosion.	Ø I			
2.	LeRC/R. Nussle	Define the total amount of each fuel to be used. Provide a toxicity assessment of each fuel and its combustion byproducts.	Ø I			
3	LeRC/R. Nussle	Prepare a hazard report addressing electro-magnetic interference.	Ø I			

ORIGINAL PAGE IS
OF POOR QUALITY

A10-21

Attachment

APPENDIX 11

APPENDIX 11

SUMMARY OF DISCUSSION AT FINAL BRIEFING (8/10/83)

This appendix is a summary of discussions during presentation at the Porous Solids Experiment Design at LeRC. The audience included Tom Labus, Ralph Nussle, Professor Berlad, Joshi (Berlad's graduate student) and Kurt Sacksteder. The notes taken are edited and reproduced below, organized by the related section of the draft report. The page of the briefing which prompted the discussion is noted and the page heading is reproduced in quotes. A section is also devoted to the post-presentation discussion. Table 1 summarizes the topics addressed in the discussions.

Table 1 SUMMARY OF DISCUSSION TOPICS

- Shuttle atmosphere (temp. pressure, gaseous constituent) effects and variations
- Use of the Shuttle cooling loop
- Ignition energy requirement
- Electrical power supply limitations
- Particle injector pressure/volume requirements; particle packaging
- Large and small scale particle mixing; eddy dissipation time constants
- Need for more detailed time history of g-loads in Shuttle bay
- Strength of diaphragms which seal tube ends
- Trapping of particles in zirconium wool ignitor
- Camera field of view/viewing stations along tube
- Resolution of flame passage by IR detectors
- Size and inertial response of unfolding balloon
- Removal of pressure transducer from instrumentation package
- Material selection for exhaust heat sink
- Power requirements of acoustic driver
- Optimal level of operator intervention
- Particle/particle and particle/wall adhesion
- Integration: procedures for installation of experiment in Shuttle
- Weight: amount of available margin

Report Section	Briefing Page
----------------	---------------

2.2	11
-----	----

"Mid-Deck Accommodations" Nussle was unsure of the partial pressure of O₂ and N₂ in the Shuttle atmosphere. Kropp summarized the nominal and worst case atmospheres. Labus wondered if the experiment might require use of the Shuttle cooling loop and whether venting would be available in the galley. Kropp replied neither would influence the design.

2.2	15
-----	----

"Mid-Deck Constraints on COPSE" Berlad requested an upper bound estimate on Shuttle atmosphere pressure and temperature variation. Kropp explained the problem is resolved through operation: the experiment is not executed during periods when Shuttle environment is out of limits defined by Berlad. Nussle questioned stringency of the 250 watt power limitation. Kropp replied it is not very tight but we designed to it. It only precluded use of very high camera framing rates.

3.3	25
-----	----

"COPSE Carousel Concept" Berlad questioned whether 16 tubes could be accommodated under weight constraint. Kropp replied they could and tube number could be reduced if necessary but our design accommodates 16.

3.4	30
-----	----

"Pressure Bottle Relationships" Nussle questioned source of particle injector pressure and volume requirements. Fleeter replied the pressure must be sufficient to burst the injector diaphragms, while the volume is required for thorough flushing of the particle cannister. Berlad wondered if any teflon was carried into the tube during injection. Fleeter responded that during test all the teflon remained attached to the diaphragm. Rather than breaking into pieces, the teflon develops tears through which the particles and air pass.

3.5	32
-----	----

"Particle Mixing Concepts" Berlad pointed out the difference between macro mixing - gross motion of the air with length scales on the order of tube dimensions, and micro mixing - motion at turbulent eddy scales. Kropp responded that injector provides macromixing and acoustic driver provides micromixing. Berlad felt a 30 sec. delay between mixing and ignition would allow dissipation of fluid motion, however particles will settle to walls due to Van Der Waals' forces and g-forces if they have a DC component (e.g. from drag forces on the Shuttle). A record of Shuttle g-loads over time is required but, according to Kropp, is not readily available nor are temperature and pressure data from the Shuttle bay. Kropp pointed out that the problem could be solved through operation -

instruction not to operate the experiment at periods of high g-loading (e.g. $> 10^{-4}$ g).

- | | | |
|-----|----|--|
| 3.5 | 33 | <p>"Acoustic Mixing Concept" Nussle questioned if diaphragm can withstand 10 lb/in² pressure and mylar is chosen for diaphragm. Fleeter responded diaphragm must</p> <ul style="list-style-type: none"> • Seal from O₂ diffusion; aluminum on mylar yields a good diffusive barrier • Be flexible to prevent resonances during acoustic mixer ops • Be light to minimize acoustic damping <p>These considerations led to mylar selection. Diaphragm thickness should be chosen to ensure sufficient burst strength.</p> |
| 3.6 | 13 | <p>"Major Science Requirements" Labus asked where 1-2 Joule ignition requirements came from. Berlad felt it was informally agreed between himself and Gat. Berlad believed nitrocellulose covered wire was the design ignitor. Kropp explained it would be zirconium wool which provides 10² times the minimum energy requirement.</p> |
| 3.6 | 35 | <p>"Ignition Concept" Berlad noted that fuel particles may become trapped in the zirconium wool. Also, how quickly will the zirconium oxidize at room temperature? How can the wool be most firmly attached to the electrodes?</p> |
| 3.7 | 37 | <p>"Photography" Berlad is considering using split field of view (FOV) at two stations along test section and <u>not</u> observing the ignition region. He prefers viewing stations 1/3 and 2/3 of test section length along tube. Fleeter pointed out this strains the film budget and suggested 3 solutions.</p> <ol style="list-style-type: none"> 1. Lower framing rate 2. Don't trigger camera until flame reaches first IR detector 3. Enlarge FOV (permits lower frame rate) |
| 3.7 | 38 | <p>"Particle Homogeneity" Berlad stressed 30 μm particle size as most important. From plot of detector range and general discussion, he determined sufficient range exists for the 30 μm case given current detector design.</p> |

Report Section	Briefing Page	
3.7	39	"Flame Rate Sensing" Berlاد questioned temporal and spatial resolution to match response curves from detectors during flame passage. Kropp and Fleeter calculated the number of response points which would be recorded and Berlاد felt that resolution provided would be adequate.
5.1	60	"Tube Component Drawings" Berlاد points out that isobaric conditions must be assured in the ignition region. It seems that even without any vent system, ignition would be isobaric simply because of the large tube volume (2050 cm ³) compared with the small ignition volume (3 cm ³).
5.3	66	"Particle Mixer" Berlاد and Joshi felt a lighter acoustic driver would suffice, and as much as 8 lb. could be saved. Fleeter pointed out that the acoustic power requirement is not well defined and the present design is more conservative. Also a metal diaphragm may be preferred over paper. Since the delivered unit was not well matched acoustically to the tube, better performance will be achieved in the flight-design hardware.
5.5	45	"COPSE Tube" Berlاد questioned how vent reservoir was sized and noted that the "inertial" properties of the vent may be important to the pressure rise in the combustion tubes. Fleeter responded that vent sizing was the result of lab experience and calculation of combustion chemistry and thermodynamics (to yield probable heat release and temperature rise) and heat losses to the tube walls and heat sinks.
5.5	64	<p>"Vent System Diagram" A general discussion on the heat sink took place. It was noted that</p> <ul style="list-style-type: none"> • Packed copper wire is an alternative to sintered Nickel • LeRC is testing a ceramic honeycomb with good results (but could it shatter?) • Nickel was chosen because it has the highest thermal diffusivity of the available materials for sintered plate. • The sintered plate thickness is limited by ΔP constraints to gain extra mass, or coarse heat sink could be added behind the sintered plate.

Report Section	Briefing Page
-------------------	------------------

- | | | |
|-----|----|---|
| 5.6 | 46 | "Comparison of Initial and Final Function" Various comments on use of a pressure transducer to document cabin pressure during run. It was felt that this would not be much help because it would not help establish partial O ₂ pressure. Further, tests could establish the tube capability to maintain 1 atm pressure while outside pressure varied. |
| 5.8 | 72 | "Typical Front Control Panel" In regard to discussion of Section 7.1, Berlad mentioned that blockage of lamps and sensors might be minimized by special treatment of small windows at their locations. Treatment might include embedded wires to carry off static charge. |
| 6.2 | 78 | "Equipment List" Nussle pointed out that mirrors and prisms should not be glass and a search might be made for best available non-shattering optics. |
| 7.1 | 71 | "Electrical Operation" A general discussion took place on the benefit of operator vs. automatic control of the decision to provide from mixing to ignition operation. While automatic control might reduce operator workload, it could delay testing if a lamp or sensor should fail or be blocked. |
| 9.1 | 83 | "Design Issues" Berlad described the impact of wall saturation by particles: <ol style="list-style-type: none"> 1) Excess particle mass should be injected to yield desired stoichiometry. 2) Instrumentation, both photographic and homogeneity detection, may be hampered. |

POST BRIEFING DISCUSSION

- Kropp stressed need to consider details of the integration process, especially max. storage duration.
- Berlad wants to load particle cannister in his laboratory to ensure accurate particle bonding. Nussle could accomplish this at LeRC.
- Nussle recommended sealing particles into a sealed pouch to eliminate double fittings for diaphragm. This will provide a longterm seal for the particles and prevent their absorption of water.
- Homogeneity and flame detectors might benefit from an overall anti-static treatment of the entire wall with special attention to the small areas at the sensor and lamp locations.
- Nussle assured Berlad that accurate, pressure measurements will be made in the ignition region of the test apparatus at LeRC.
- Nussle questioned the total weight and how it may be trimmed. Fleeter responded that potential savings are available in
 - 1) Thinner tubes
 - 2) Use of titanium for structure instead of aluminum
 - 3) Move electronics and the recorder to a separate location.
- Will noise be a problem during mixing? Fleeter pointed out that noise will be reduced compared to the lab apparatus because
 - 1) Polycarbonate is a better damper than glass
 - 2) Better seals will reduce sound emission
 - 3) Experiment has an outer housing which will further enhance the sound
 - 4) Somewhat lower power may be required with a better acoustic impedance match.

- Berlad and Labus suggested a graduated level mixing strategy. As mixing progresses the sound level is gradually decreased so that at the end of mixing only a very short time is required for dissipation of remaining fluid motion.

- A vibration analysis should be made - the injector pressure bottles may need to be made rigid to withstand launch.